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Sedimentary Archives of Downstream Energy Fluctuations on the Kangaroo River of NSW

Brett Rowling
University of Wollongong

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Abstract

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Five sites were selected at key points along the length of the river. A Global Positioning System (GPS) was used to record precise locations. Surveys were conducted at all sites using Light Detection and Ranging (LiDAR) wherever possible. At alluvial sites, sediment was collected by augering or taking core samples. Collected material was later analysed for grain size using a Malvern Mastersizer 2000 and for mineralogy using X-ray diffraction (XRD). Cobble size was measured using the Wolman series. Samples from two sites were also subjected to Optically Stimulated Luminescence (OSL) to date past geomorphic events and a charcoal fragment from one of these sites was radio radiocarbon dated.

Sedimentary results indicated that each site responded differently to fluctuating energy levels and that the response pattern was dictated by changing structural controls. The valley floor widens and narrows as it flows through harder and softer units, altering the dominant mode of flood plain accretion. Mineralogy of the terrace alluvium reflected the composition of the geological units through which the river has flowed.

Five OSL dates were obtained from two alluvial sites and their ages were late Holocene ranging between ~ 3.5 – 1.6 ka. The one radiocarbon date was mid Holocene at ~ 5.9 ka and was thought to have been incorporated in the terrace following fluviatile remobilisation. The absence of Pleistocene sediments like those in adjacent coastal valleys suggests that the combination of a very small catchment size, low channel to floodplain width and high intensity rain events has limited the Kangaroo River's sedimentary history. Because of the small range of these dates, it was difficult to conclude whether they represented the first deposition immediately following the Holocene Climatic Optimum or whether they were the product of local climatic events.

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By Brett Rowling

2010

A thesis submitted in part fulfilment of the requirements of the Honours degree of Bachelor of Science in the School of Earth and Environmental Sciences, University of Wollongong 2010.

The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

Signed: __________________________________ Date: ___________________

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To my family and friends who are last on the list but first to be there when in need.

CHAPTER 1

Introduction

1.1 Geographical Setting

Kangaroo Valley is located approximately 200 kilometres south of Sydney (Figure 1.1). The Kangaroo River rises 10 km south east of Robertson on the Southern Highlands plateau. The river then plunges over the escarpment, flows through a deep incised gorge, crosses a steadily widening floodplain, before partially incising again near its confluence with the Shoalhaven River at Tallowa.

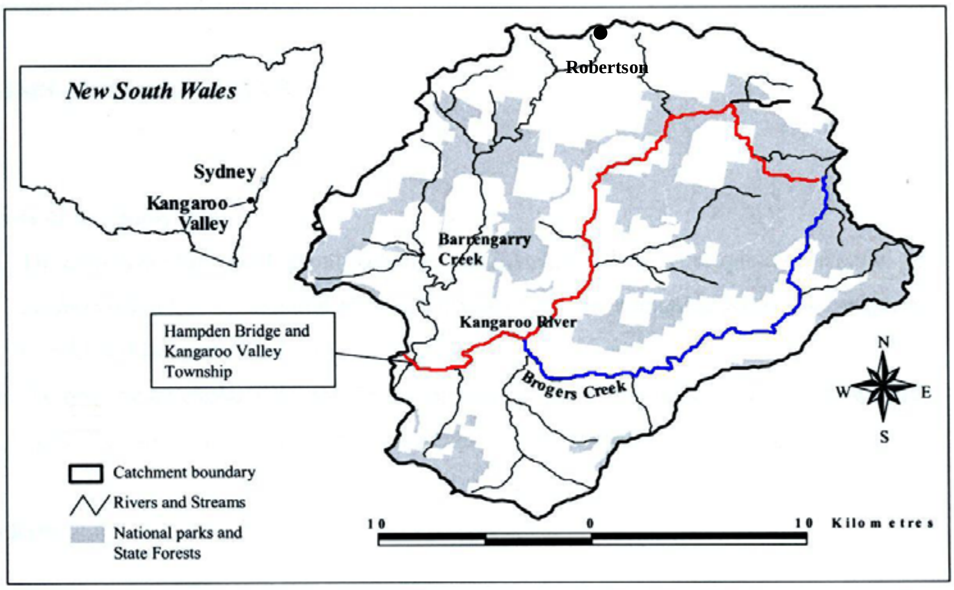


Figure 1.1: Locality Map (Brown, 2002)

The upper reach is characterised by a preponderance of natural bushland, which changes to cleared grazing land on the broader floodplain and foot hills. Natural vegetation returns in the lower incised reach as the confluence is approached (Figure 1.2).

Figure 1.2: Kangaroo Valley looking east from Mannings Lookout, showing natural vegetation on the plateau and slopes with agriculture on the valley floor.

1.2 Rationale for Study

The impact of late Quaternary climatic fluctuations on terrace formation, along the east coast rivers of Australia, has shown a consistent pattern (Nanson et al., 2003). Research has focussed on rivers with relatively large catchments, including the Upper Shoalhaven River (Page et al., 2007) and the Lachlan River (Kemp and Rhodes, 2010). However, the formation and preservation of terraces in partially confined valleys has received scant attention and is therefore less understood (Cohen and Nanson, 2008).

This study hopes to contribute to the knowledge of late Quaternary terrace formation, by studying the fluvial history of the Kangaroo River in the small, partially confined Kangaroo Valley. The river has a very high discharge rate (Young, 1974; Brown, 2002) and this, coupled with the high intensity rain events which characterise the region (Nanson and Hean, 1985; Reinfelds and Nanson, 2001), make the valley vulnerable to periodic flooding (Bayley, 1965; Hilder, 1988). The combination of confinement, high discharge rates and flooding made the Kangaroo River a distinctive river for the study of terrace formation.

The only radiocarbon date from a terrace in the Kangaroo Valley was late Holocene with an age of ~1790 +/- 90BP (Young, 1976), suggesting that any terraces in the valley will be comparatively young. However, mineralogy from the surrounding area shows a high clay content, in particular kaolin and this would suggest that the terraces may be much older (Bowman, 1974). Therefore, the chronology of basal terrace formation within the Kangaroo Valley was an important aspect of this study.

1.3 Aims and Objectives

Aims

The broad aim of the study was to develop a detailed history of changing fluvial conditions along the length of the Kangaroo River and relate these to changes in the contemporary landscape.

The specific aims were to:

1. Determine how the form and processes of the Kangaroo River have changed throughout the late Quaternary.
2. Develop a timescale and identify the reasons for these changes.
3. Compare the results against the recent studies from other rivers of southeast Australia throughout the late Quaternary.

Objectives

In order to achieve these aims, the objectives were to:

1. Review the relevant literature.
2. Determine the broad morphological characteristics of each site.
3. Analyse river sediment from all alluvial sites using a variety of techniques to identify weathering products and stratigraphic units.
4. Relate field based observations and first hand evidence about the current river's characteristics, in order to understand the range of conditions that have prevailed in the past.
5. OSL and radiocarbon date from an exposure and auger samples to obtain a timescale of prior conditions.

1.4 Scope and Outline of Study

Five sites were studied at key locations along the length of the Kangaroo River. Their position and characteristics are presented in Figure 1.3.

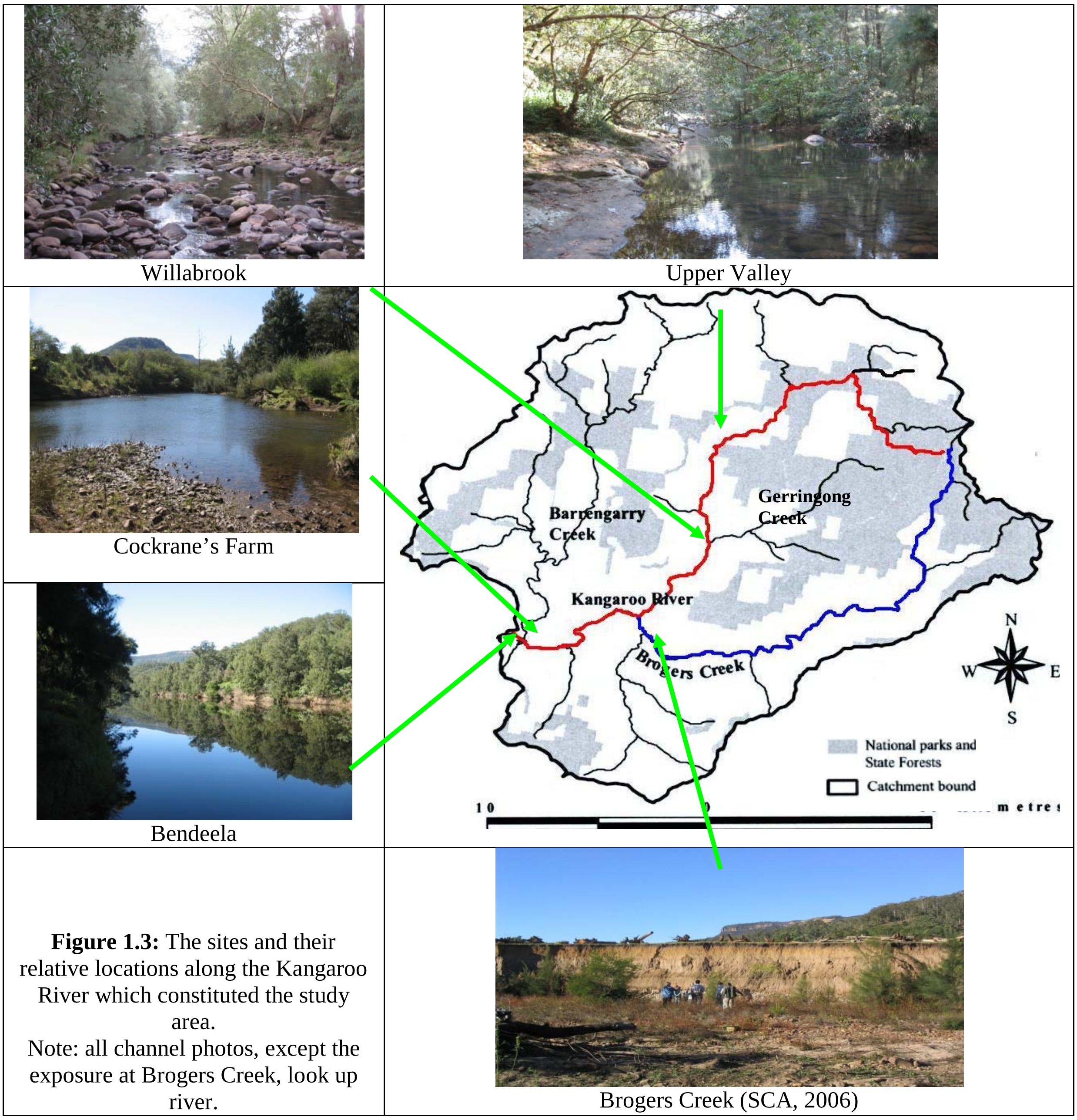


Figure 1.3: The sites and their relative locations along the Kangaroo River which constituted the study area.
Note: all channel photos, except the exposure at Brogers Creek, look up river.

In the study of the Kangaroo River's fluvial history, a number of variables were examined in detail. Fluvial sediment was analysed for grainsize, mineralogy and relative organic constituents. The mode of terrace development at four discontinuous terrace sequences was investigated. The basal age at two terraces was also established.

Chapter 2 places the present study into its regional context and provides a detailed description of the region's physical attributes including catchment, climate, hydrology, geology, soils and vegetation. Chapter 3 reviews the relevant literature to this study. This includes a brief history of earlier research in the region, a discussion of the processes associated with floodplain and terrace formation and an outline of the late Quaternary evolution of NSW coastal rivers. Chapter 4 combines the methods and results. Each section comprises information about the technique being used and, the results obtained. Chapter 5 provides a thorough discussion of each aspect of the results, including the downstream changes in energy and mineralogy, alteration in the dominant mode of floodplain development and the importance of structural controls on terrace formation and preservation. The implications of the terrace ages for late Quaternary climatic fluctuation are also discussed and the thesis concludes with a summary of the main findings.

CHAPTER 2

Regional Setting

2.1 Catchment

The Kangaroo River has a catchment of 330 km^2 with a dendritic drainage pattern (Ollier and Pain, 1994). The three main tributaries are Gerringong, Brogers and Barrengarry Creeks, which join the Kangaroo River in that order as it flows downstream. The Kangaroo River forms part of the Shoalhaven Water Scheme, which provides water and hydroelectricity to the local communities. It also provides water to the Sydney region during drought and electricity to the NSW grid in times of peak demand (SCA, 2007).

2.2 Local Climate and Hydrology

The Kangaroo Valley and Southern Highlands region experience a warm, temperate climate. Prevailing winds are from the south and northeast during summer and from the west and south west in winter, with rainfall being influenced by an orographic effect. This means that the plateau receives approximately 500 mm per annum more than Kangaroo Valley (Table 2.1).

	Caalong St, Robertson	**Kangaroo Valley**
Station Number	68054	68036
Commencement and Status	1890, Open	1914, Open
Elevation	756 m	85 m
Distance Inland	23.6 km	21.8 km
Max Ave Daily Temp	25.5 °C (Feb)	28.3 °C (Feb)
Min Ave Daily Temp	11.1 °C (July)	10.4 °C (July)
Average Rainfall	1830 mm	1266 mm

Table 2.1: Average Climate Statistics (BOM, 2010).

Both the historical records and, more recently, the gauged data show that floods are a periodic occurrence in Kangaroo Valley. Bayley (1965) reports, that the Kangaroo River rose 55 feet and washed the old bridge away, in the devastating flood of 1898. Hilder (1988) reports on deaths and losses in the floods of the early twentieth century. Since 1966, when the flood gauge was opened at Hampden Bridge (Station

Number 215220), the records have continued to show clusters of floods interspersed with drier periods (Figure 2.1).

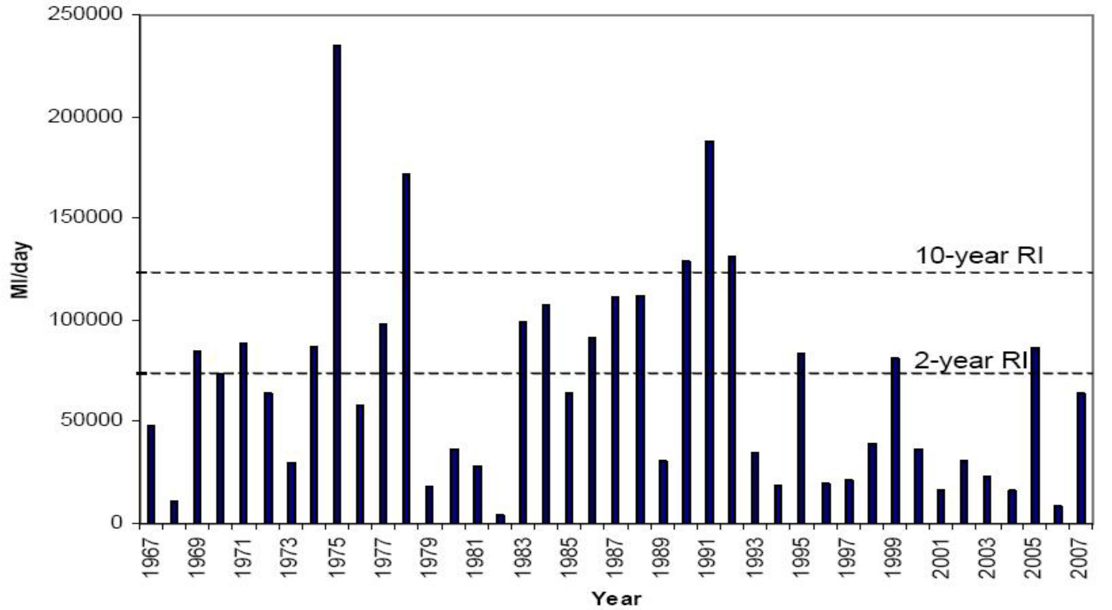


Figure 2.1: Instantaneous Discharge Values from SCA Hampden Bridge Gauge; Converted to total discharge over a 24 hour period (Cohen, 2008).

The Southern Highlands plateau is characterised by frequent, intense, single rain events (Young and Nanson, 1982) and flooding within the valley is associated with these events. Examination of a ten year period from 1974 to 1984 shows that, even within this short window, five high intensity rain storms were recorded at Robertson and these all caused flood events within the Kangaroo Valley (Table 2.2).

Flooding in Kangaroo River: 1974 - 1984				
Month/Year	**Total Rainfall Kangaroo Valley (mm)**	**Total Rainfall Robertson (mm)**	**Duration (Days)**	**Discharge (ML/day) Hampton Gorge**
August 1974	284.0	602.2	2	95300.3
June 1975	443.9	461.0	2	123175.2
October, 1976	236.6	185.0	3	51233.3
March 1978	563.3	883.0	3	186027.8
November 1984	221.1	268.2	3	57128.7

Table 2.2: Daily Rainfall Totals (BOM, 2010) and Total Daily Discharge (SCA, 2010).

The Shoalhaven City Council (2006) has identified Kangaroo Valley as a high risk site and has completed a preliminary flood study. However, a flood risk management programme for the valley is yet to be undertaken (Ghetti, 2010).

2.3 Local Geology

Geologically the Kangaroo Valley is incised into the Sydney Basin which consists of a sub-horizontal sequence of Permian and Triassic, fluvial and marine sediments with intrusions and extrusions of Tertiary basalts (Bowman, 1974). Table 2.3 below provides a stratigraphic summary of the formation and characteristics of each unit.

Period	Geological Unit	Formation and Characteristics
Tertiary	Tertiary Volcanics (65-5 Ma)	Basaltic lava, which has flowed over the landscape, from intrusions through the units.
Triassic	Hawkesbury Sandstone (251 - 205 Ma)	Medium to coarse grained quartzose sandstone, tending to fine upwards and of fluvial origin.
	Narrabeen Sequence (253 - 251 Ma)	Inter-bedded sand and mud sequences from a combination of fluvial and marine influences.
Permian	Illawarra Coal measures (264 – 253 Ma)	Fine muds and silts, deposited under fluvio-deltaic, low energy, anoxic conditions.
	Shoalhaven Group	
	Budgong Sandstone (263 - 264 Ma)	Reddish to yellow/brown lithic sandstone, deposited on a delta fringe.
	Berry Siltstone (265 – 264 Ma)	Dark grey siltstone, coarsening upwards into laminate, sandy phases-of possible deltaic origin.
	Nowra sandstone (267 - 265 Ma).	Coarse, pebbly quartzose sandstone deposited under transgressive, marine conditions consistent with a vertically fining sequence.
	Wandrawandian siltstone (273 – 267 Ma)	Fine grained silt, containing fossils and drop stones, suggesting a shallow marine setting with sea ice.

Table 2.3: Geological Units of the Region from Bowman, 1974.

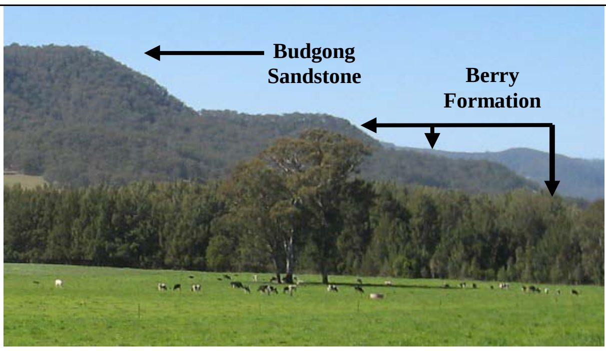


Figure 2.2: Benching of the Valley.

The depositional pattern and relative strengths of the different units has influenced the geomorphology of Kangaroo Valley (Young, 1977; Young and Young, 2007). The erosion resistant, mechanically strong unit of the Hawkesbury Sandstone has formed near vertical cliffs and narrow gorges around the edge of the plateau. Immediately below this are the steep, talus slopes, partly mantling of the Narrabeen Series and Illawarra Coal Measures. Further down, the Budgong Sandstone forms another prominent cliff line, below which the siltstones of the Berry Formation have produced a series of gentler slopes and benches, along the sides of the Kangaroo Valley (Figure 2.2). Beneath these formations, the Nowra Sandstone, another erosion resistant and mechanically strong member, has formed a secondary plateau-the Brookes Plateau. This unit has subsequently been incised by the Kangaroo River, creating another narrow gorge with high vertical cliffs. Below the Nowra Sandstone, the valley widens again and slopes gently from the exposure of Wandrawandian Siltstone (Bowman, 1974).

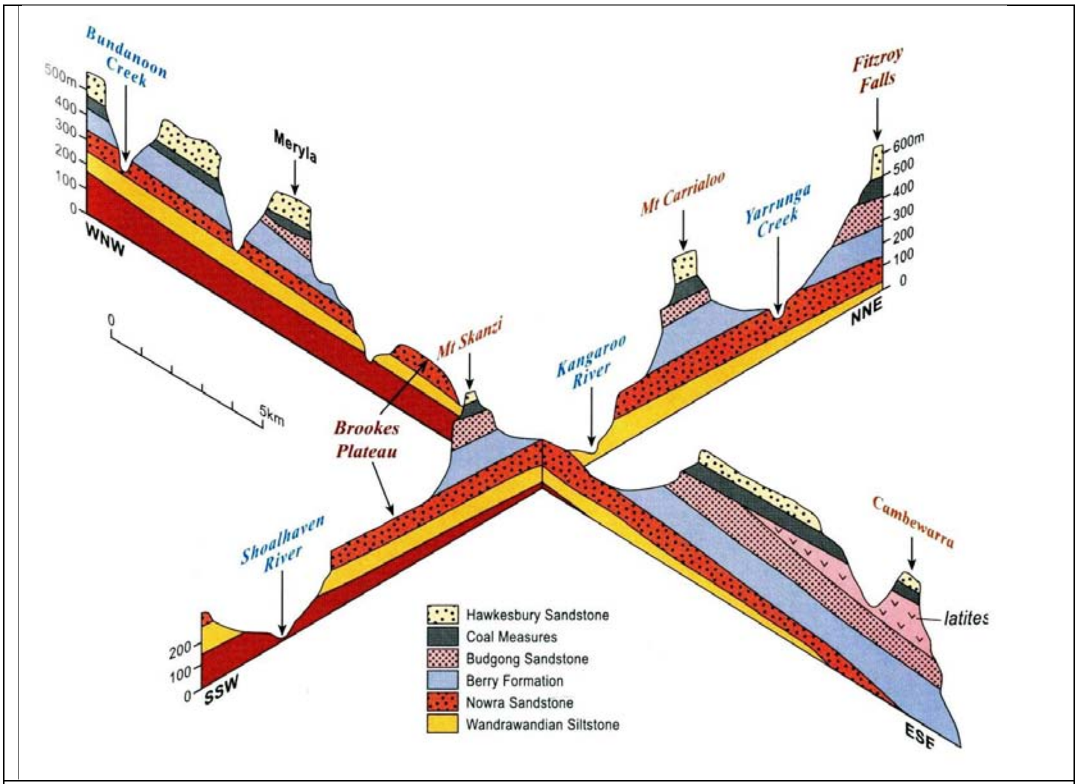


Figure 2.3: Dip of Geological Units of the Region (Young and Young, 2007).

These benches follow the regional stratigraphic dip, rising gradually down valley to the south west. At the same time, the gently dipping Permian sediments thicken from west to east (Figure 2.3).

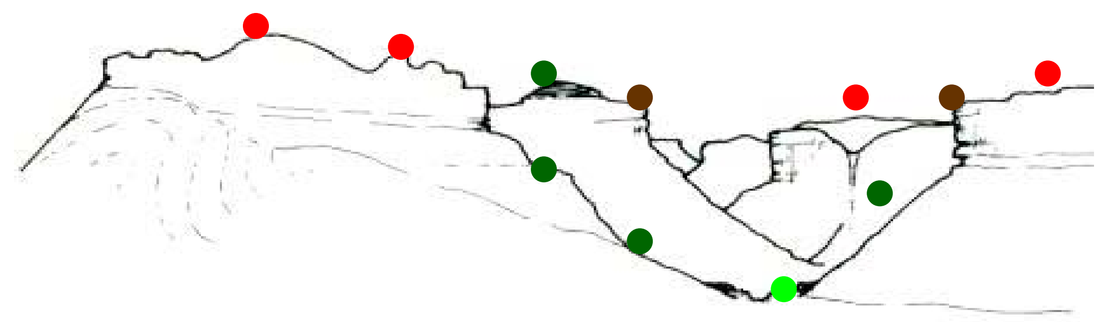
2.4 Local Soils and Vegetation

Vegetation within the Kangaroo Valley is diverse (Figure 2.4), consisting of many habitats and species due to variations in local geology, landforms, soils and climate (Hazleton, 1992).

On the plateau, Hawkesbury Sandstone sustains some of the least dense native vegetation, as it has formed yellow Podzolic soils, which are generally less than 50 cm in depth, low in mineral nutrients and organic material. However, these conditions are ideal for dry forests of *Eucalyptus globoidea*, while small pockets of heath land containing *Eucalyptus gummifera* occur in drainage depressions, where Gleyed Podzolic soils are commonly formed. Simple rainforests, consisting of Coachwood (Ceratopetalum *apetalum)* and Sassafrass *(Doryphora sassafras),* are largely confined to the small remnants of basalt flows and Wianamatta shale, which form red Krasnozems (Black, 1988; Fox, 1988; Hazelton, 1992).

The slopes generally form soils of ~ 150 cm in depth. Talus forms a brown Podzolic soil, the Budgong formation produces red and yellow Podzolic soils, while the Berry grades from a Krasnozem at the top to a Xanthozem at the bottom (Hazelton, 1992). These varied soils sustain different types of vegetation depending on the microclimate. In the secluded slopes of the valley, rainforests containing Red Cedar *(Toona australis)* and Lilly Pilly *(Acmena smithii)* flourish on brown Xanthozems while the drier areas support an open forest containing *Eucalyptus agglomerate* and *Eucalyptus punctata* (Black, 1988; Hazelton, 1992).

In the valley, riparian vegetation consisting of Casuarinas *(Casuarina cunninghamiana)* predominates within and along the river channel. Soils vary from poorly sorted and rocky in the upper reaches to well developed, deep clay soils of ~ 250 cm on the undulating floodplain, with soils changing from Gleyed Podzolic on the lower terraces to yellow Podzolic on the higher terraces (Fox, 1988).



System	Geological	Soil Type and Fertility	Vegetation Species
Rainforest	Tertiary Volcanics, Shales and Mudstones	Highly fertile Krasnozem and Xanthozem	*Ceratopetalum apetalum and Doryphora sassafras*
Plateau	Triassic and Permian Sandstones	Low fertility sandy yellow Podzolic soils	*Eucalyptus globoidea/gummifera*
Heath land	Sandstone Depressions	Low fertility Gleyed Podzolic soils	*Eucalyptus consideniana/stricta*
Riverine	Sedimentary	Highly fertile, Gleyed to yellow Podzolic soils	*Casuarina cunninghamiana*

Figure 2.4: Summary of Vegetation Communities (Adapted from Black, 1988).

CHAPTER 3
Literature Review

3.1 Introduction

This chapter reviews previous studies in Kangaroo Valley as well as the valley's geological evolution, so that the present study can be placed into its geographic and historic context. This is followed by a discussion of the forms, processes and energy changes in fluvial systems. The impact of climatic fluctuations on river flows in southeast Australia is then considered throughout the late Quaternary.

3.2 Previous Studies in Kangaroo Valley

Since Europeans arrived in Australia, scientists have been interested in understanding how the deeply dissected plateau of the Southern Highlands was formed. Throughout the nineteenth century, debate centred on whether the sea or the rivers had sculptured the abundant cliff lines. "Father of Australian Geology", the Reverend W. B. Clarke (cited in Young, 1974), believed that Kangaroo Valley had once been a freshwater lake, which had burst through its barriers. On his first visit to Kangaroo Valley, James Dana, prominent American geologist, thought that the sea had once occupied the valley as a "gulph" (cited in Mozeley 1964) but later decided that the "running water" of streams had created the landforms (Dana, 1850).

By the conclusion of the nineteenth century, it was generally accepted that the gorges had been carved by the rivers (David, 1896). The next sixty years saw geologists searching for a theory, which could explain the development of the landscape in more detail and provide a time frame for its formation. The most widely accepted theory was based on the Davisian model of cyclical planation or erosion (Davis, 1902). A number of theorists, including South African geologist, L.C. King (1959), proposed that the plateau of southeastern Australia had been formed by extensive mid Tertiary planation, followed by uplift and gorge incision at the end of the Tertiary. For these theorists, this was a youthful landscape of fast, flowing streams with plateau surfaces of Miocene age (King, 1959; Geyl, 1961).

To this point in time, geologists had developed their theories based only on observation of surface landforms and their beliefs lacked a sound, empirical basis (Summerfield, 1991). However, the 1970's saw a change in focus with geologists looking beneath the surface for a more precise explanation of the geomorphology. A number of geological surveys provided detailed information about the characteristics of the region's stratigraphy (Bowman, 1974; Herbert and Helby, 1980). Potassium-Argon dating showed that the basalts of the plateau surfaces were not Miocene, but Eocene in age (Wellman and McDougall, 1974).

In this context, Young (1977) approached the development of the Shoalhaven region with a new scientific rigor. He meticulously dissected the landscape, assessed the contribution from each part and then systematically reconstructed the regional history. From his examination of the lithology, structure and drainage patterns, he concluded that the landforms of the region were the result of deep erosion of a complex lithology. Using Wellman and McDougall's (1974) Eocene and Oligocene dates for the basaltic contours, Young (1977) proved, that uplift was well underway by the early Tertiary and completed by the Oligocene. From his research, Young (1977) concluded that the Kangaroo River's course was dictated by structural constraints.

Towards the close of the twentieth century, the relative rates of erosion of different landforms within the Shoalhaven catchment were calculated using the K-Ar dates from newly discovered Tertiary basalt flows within fluvial gorges (Bishop et al., 1985; Nott et al., 1996). These studies showed, that denudation was not uniform across all landforms but was maximal at the head of the gorges, where fluvial activity was accelerating erosion. Their studies concluded, that the Southern Highlands plateau will become more dissected, before either scarp retreat or summit lowering has any appreciable impact on the landscape (Bishop et al., 1985; Nott et al., 1996).

Figure 3.1: Remediation at Brogers Creek Exposure (SCA, 2006).

In the twenty first century, the focus of research has moved to river management, because of Kangaroo River's strategic location, as part of the catchment for Tallowa Dam. Brown (2002) identified several key factors, which accelerated channel erosion. These included the removal of riparian vegetation and woody debris, as well as cattle trampling along river banks. Sydney Catchment Authority implemented some of her recommendations, including bank stabilisation at a sensitive site on Brogers Creek (Figure 3.1).

Today, the SCA (2006) regularly monitors the river and its tributaries, working with local landowners to reduce the risk of further erosion, thereby keeping sediment loads to a minimum. The importance of this work was highlighted by Cohen's 2008 report for the Southern Rivers Catchment Management Authority (SRCMA), which showed that further erosion had occurred at the Brogers Creek site, despite bank stabilisation work.

With the development of luminescence dating, the potential for establishing a chronological record from river terraces has been increasingly recognised (Tsukomoto et al., 2009). However, recent studies examining the late Quaternary history of the area using these techniques have focussed on the neighbouring Shoalhaven River (Nott, et al., 2002; Kermode, 2007) and the Nepean River (Nanson et al., 2003).

At Bendeela, ~ 7 km downstream from the Hampden Bridge, Young (1976) dated some charcoal fragments from the lower terrace prior to its flooding by the Tallowa Dam. At the time, this terrace was about seven metres above the river channel. The fragments were radiocarbon dated at 1710 +/- 90BP and Young believed that they were associated with a distinct depositional phase within the Illawarra region. To this point in time, Young's single radiocarbon date remains the only date for any fluvial sediment within the valley.

3.3 A Step Back In Time-The Formation of Kangaroo Valley

Kangaroo Valley is localised within the Southern Sydney Basin, a depression, which filled with sediment derived from the Lachlan Fold Belt during the Permian and Triassic periods ~ 300 - 250 Ma (Branagan and Packham, 2000). Initially the beds were laid down horizontally however rifting of New Zealand from Australia caused a gentle uplift, which was both epeirogenic and asymmetric in nature (Branagan and Packham, 2000). Fission track dating indicates that the uplift probably occurred between 80 – 100 Ma (Dumitru et al., 1991) and K - Ar dating shows that uplift was almost certainly complete by 65 Ma (Young, 1983). Erosion of material over the gentle slopes to the west and steeper slopes to the east began carving valleys and dissecting gorges (Ollier and Pain, 1994).

Small pockets of volcanism occurred around 50-30 Ma and the basaltic lava flowed over the plateau surface and down into the valleys. Sometimes the lava filled old river channels causing an inversion of relief, with rivers forced to carve new channels (Nott et al., 1996; Young and Young, 2007).

Since 90 Ma, there has been minimal tectonic activity in the region (Murray-Wallace, 2002) and the existing rock layers have continued to erode slowly at variable rates, according to their position in the landscape. (Table 3.1) (Nott et al., 1996).

Erosion Type	Erosion Rate
Gorge Extension	2500 m /Ma
Gorge Side Wall Retreat	< 0.3 m/Ma
Plateau Stream Incision	0.17 m/Ma
Major Escarpment Retreat	170 m/Ma

Table 3.1: Shoalhaven Catchment Erosion

3.4 On the Plateau - Down Wearing

The headwaters of the Kangaroo River are located upon the Southern Highlands plateau. Shallow swamps and dells have formed within depressions on the Hawkesbury Sandstone. These have accumulated water and other sediments over thousands of years (Young, 1987). During the intense rain events that occasionally engulf the region (Nanson and Hean, 1985; Reinfelds and Nanson, 2001), excess water from these depressions flows overland to the main channel, transporting a relatively low sediment loads (Young and Young, 2007).

3.5 The Falls - Back Wearing and Gorge Extension

At the abrupt edge of the escarpment above Kangaroo Valley, Carrington Falls dissipates the most energy of any point along the river (Young, 1985). The classic Niagara model suggests that undercutting is a key feature of most waterfalls due to differing mechanical strengths (Gilbert, 1896). However, at Carrington Falls (Figure 3.2) the water plunges over erosion resistant Hawkesbury Sandstone for the entire descent and the falls are buttressed like a dam at the base, so that undercutting

Figure 3.2: Carrington Falls
C: no undercutting ;
A and B: buttressing
(Young, 1985)

is not possible. Fluvial extension occurs, as sheets of sandstone carve off along the joint planes of the unit (Young, 1985).

A long, narrow gorge has incised downstream, because the high erosive energy of the Carrington Falls means that the gorge extends much more rapidly than it widens out. Eroded material from this process adds a small, but steady sediment supply to the river (Nott et al., 1996).

3.6 Bedrock Reaches

Bedrock reaches are most frequently found in the headwaters, where the river is confined between bare rock cliffs and erodes vertically into a bed rock channel (Bull, 1979). However, a bedrock-river seldom exhibits channel boundaries formed by bare bedrock throughout its entire length. Instead, reaches of boulder bed and bedrock channel often alternate with stretches of shallow alluvium (Bull, 1979; Knighton, 1998).

Along bedrock reaches, a variety of erosional processes can occur with the dominant process depending on the substrate lithology. If the channel bed is dissected, then chemical and physical erosion contribute to the loosening and plucking of joint blocks in turbulent flows. If the bed is massive, abrasion by suspended load and cavitation predominate (Wende, 1999; Whipple et al., 2000).

Distinctive depositional bed forms result in the lower energy reaches. As the gradient and energy decrease downstream, transport capacity is reduced resulting in traction clogging (Carling and Davison, 1996). Cluster bed forms may develop around the traction block with boulders being imbricated on the stoss while smaller particles congregate on the lee side (Knighton, 1998; Wende, 1999). The Wolman (1954) series provides a simple, field technique to quantify in channel boulder dimensions. The long term break down of clasts continues, with further collision and abrasion from suspended material within the river and the rate at which the breakdown occurs can be quantified using Annandale’s erodability classification (1995).

3.7 Floodplain Formation

The classic theory of floodplain development was put forward by Mackin (1937) and later by Leopold and Wolman (1957), who proposed that floodplains form primarily by the lateral accretion of sediment and that vertical accretion only adds a fine top layer of over bank deposits. The problem with this theory is that it was developed on meandering rivers and its applicability to other types of rivers has since been found wanting (Schumm, 1977).

Schumm and Lichty (1963), working on the Cimarron River in Kansas found that after an episode of severe erosion, the river formed a new floodplain largely by vertical accretion. Only after this stage was completed, did lateral accretion occur. On the coastal rivers of the Illawarra, Young and Nanson (1982) found that the mode of floodplain development changed from lateral upstream to vertical downstream accretion as the rivers' gradients decreased. They concluded that the combination of low gradients and, therefore stream power, coupled with high resistance from banks of cohesive mud prevented these rivers from migrating.

Nanson and Croke (1992) developed a classification of floodplains into three groups, based on the relationship between stream power and the erosional resistance of the channel. In brief, as the energy of the stream decreases, the sediment shifts from non cohesive to cohesive and with this there is a change from lateral to vertical accretion. They stress the importance of recognizing that changes in the environment mean the depositional pattern will shift from one type of accretion to the other (Figure 3.3).

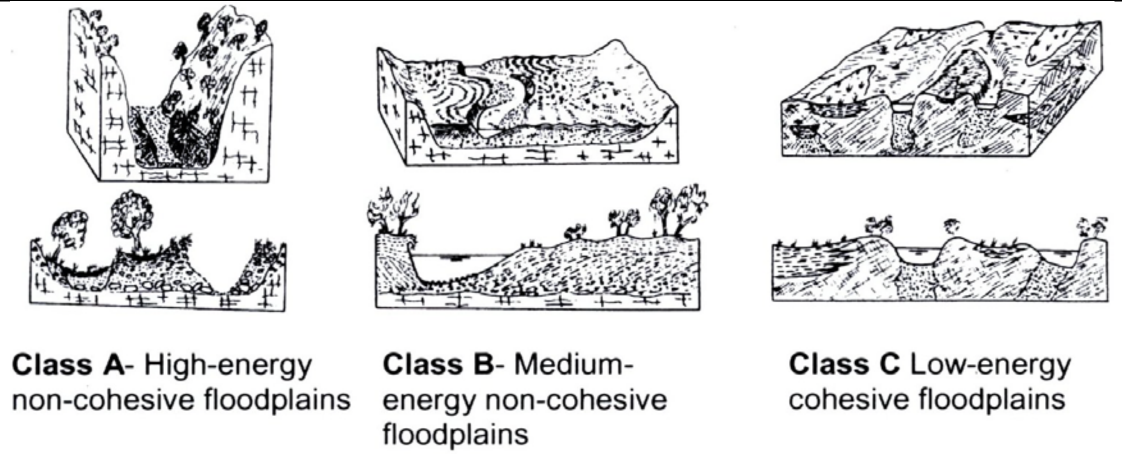


Figure 3.3: Floodplain Classification (Nanson and Croke, 1992).

In their work on the Tuross River, Ferguson and Brierley (1999) generally confirmed Nanson and Croke's theory (1992). However, where the floodplain width exceeded 700 metres, the relationship between stream power and floodplain style broke down and auto-cyclic processes, such as channel migration became the controlling factors.

3.8 The River Terrace

Terraces are a common feature along river banks and can sometimes provide useful information about past flow regimes. However, such an apparently simple and straightforward feature can be difficult to interpret and define (Warner, 1972; Chandra at al., 2007).

A terrace is essentially a palaeo-floodplain and, as such, its separation from the present floodplain usually results from a change in the behaviour of the river (Knighton, 1998). However, there is disagreement about exactly what causes the terrace to develop. For instance, Schumm (1977) argues that climate is the driving force, Bull (1991) suggests that a variety of environmental changes can be important, Young and Nanson (1982) showed that the intrinsic characteristics of a river system can control terrace development while Cheetham et al. (2010), found that both climate and local processes influenced terrace formation.

There have been a number of attempts to develop a simple classification of terraces based on the frequency of flooding, soil development and height above the river (Warner, 1972, Walker and Coventry, 1976). However, Cohen (2003) and Cohen and Nanson (2008) found that this type of classification can be inadequate, because variables such as river discharge, sediment load and the erosion resistance of the alluvium all need to be taken into account.

In an ideal situation, one sediment layer is deposited directly above the previous layer laterally, vertically or obliquely with no loss of material (Brierley and Fryirs, 2005). In addition to the sediment, certain features within the layers may also provide information about the history of the terrace. Mottling may be used to indicate relative age with soil horizons being used to correlate contemporary events (e.g. Warner, 1972; Walker and Coventry, 1976). Woody debris including charcoal may provide material to carbon date a terrace (Young, 1976), while quartz and other minerals can be used for luminescence dating (Walker, 2005).

3.9 Restrictions on Terrace Formation

In reality, many factors can either distort or limit the history contained within the terrace. If a higher flow regime follows terrace formation, much of the earlier material can often be washed away (Warner, 1972; Wende, 1999) while high levels of bioturbation can disrupt the stratigraphy in frequently flooded low level terraces (Walker and Coventry, 1976).

The size of the river, relative to the size of its valley, will also determine the storage space and therefore, the time period over which a terrace can be retained. In the lower reaches, the river has a larger area in which to deposit and store material and this material can be used to evaluate past climate conditions (Warner, 1972; Nanson et al, 2003). However, in confined bedrock river valleys, terraces are readily eroded and tend to remain only in protected locations (Bull, 1979).

Structural controls can impose permanent constraints on a river and this impacts on where terraces can form (Reinfelds et al., 2004). On the Shoalhaven River, the flight of Larbett terraces has been preserved, because of its protected location downstream of a confining, Silurian dacite gorge (Nott et al., 2002) while, on the Bellinger River, stepped terraces of Pleistocene age have been preserved on the lee side of bedrock spurs (Cohen and Nanson, 2008). (Figure 3.4).

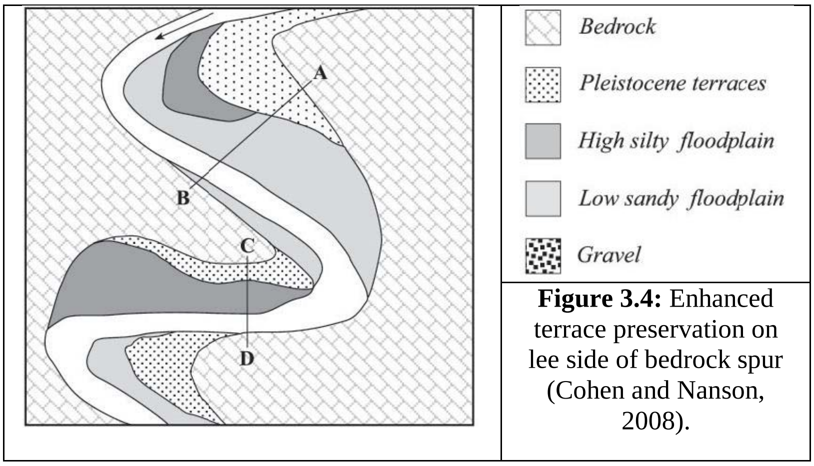


Figure 3.4: Enhanced terrace preservation on lee side of bedrock spur (Cohen and Nanson, 2008).

3.10 Geomorphic Thresholds

Early theorists (eg Davis, 1902) believed that rivers changed their form to attain equilibrium, which is defined as a condition of balance between the processes operating in a fluvial system. However, Bull (1991) has argued that rivers seldom reach an equilibrium state and, if they do, the condition only lasts for a short period of time. Nanson and Erskine (1988) have argued that the coastal rivers of NSW would always be characterised by disequilibrium, because of the region's frequent flood events.

Schumm (1977) and Bull (1991) propose that the concept of geomorphic threshold provides a better understanding of the relationship between process and form in river systems. Essentially, a geomorphic threshold can be considered as the tipping point between two alternative modes of operation, with energy fluctuations producing such adjustments.

Bull's threshold of critical power (1979; 1991) uses a simple ratio of stream power to resisting power to provide a quantitative means for determining, which mode of operation will prevail. In practical terms, this information can be used to determine the time frame and location of sediment deposition or erosion.

Ultimately however, for any event on any river, what must be determined is whether the river's change in behaviour has occurred because the geomorphic threshold has been exceeded or because external factors such as climate have altered (Young, 1976).

3.11 Rivers of South Eastern Australia: Response to Quaternary Climatic Changes

Throughout the mid to late Quaternary, south eastern Australia appears to have alternated between wetter and drier periods (Nanson et al 1992). During pluvial periods, the re-energised rivers were able to cut larger channels and transported coarser sediment. Bedrock rivers had material scoured and this material was overlain on top of past terraces (Warner, 1972; Nanson et al., 2003), whereas during drier times the sediment load became finer and channels narrowed and straightened (Kemp, 2004).

Sediment analysis from a number of different rivers from other parts of south eastern Australia has shown a consistent timescale for this climate oscillation. Evidence from terraces on the Shoalhaven River (Nott et al., 2002; Kermode, 2007), the Nepean River (Nanson et al., 2003), palaeochannels along the Lachlan River and Southern Murray-Darling Basin (Kemp, 2004; Kemp and Rhodes, 2010) as well as the Murrumbidgee sector on the Riverine Plain (Page et al., 2007) all provide a roughly similar chronological sequence for these flow regime changes. This is despite the fact, that these rivers flow in different directions and have different flow regimes.

A schematic summary of the key findings from a number of studies indicates that over the past 130 ka there has been a general drying trend with fluvial periods becoming shorter and less intense (Figure 3.5).

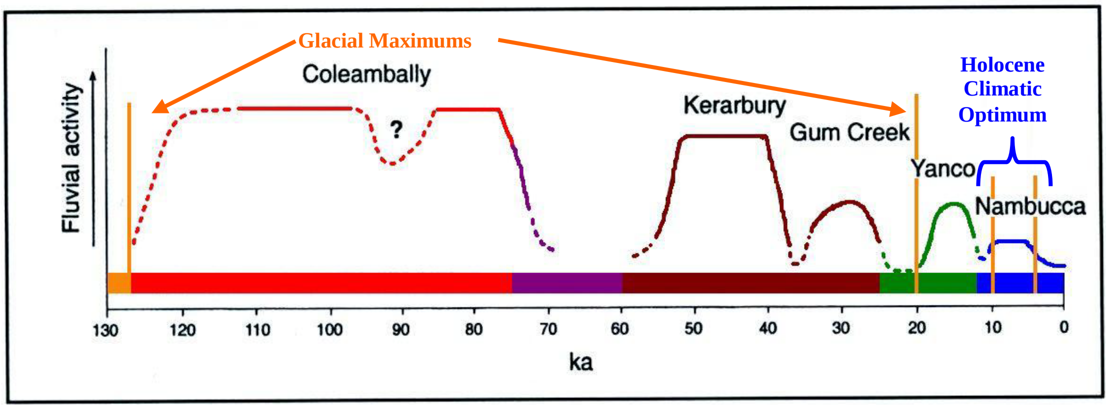


Figure 3.5: Timeline of Fluvial Activity (modified from Nanson et al., 2003).
Key: OIS 5 OIS 4 OIS 3 OIS 2 OIS 1

The history from small, partially confined river valleys has been shorter and the role of these broad climatic periods in terrace formation has been less consistent. Results from the Bellinger River on the North Coast (Cohen and Nanson, 2008) and from the Widden Brook in the Upper Hunter Region (Cheetham et al., 2010) suggest that terrace formation occurred in response to a combination of broad climatic influence and the exceedence of intrinsic thresholds while on the Clyde River, Wray et al. (2001) concluded that Holocene terrace formation was solely due to local processes. Refer to Figure 3.6 for approximate positions of the rivers.

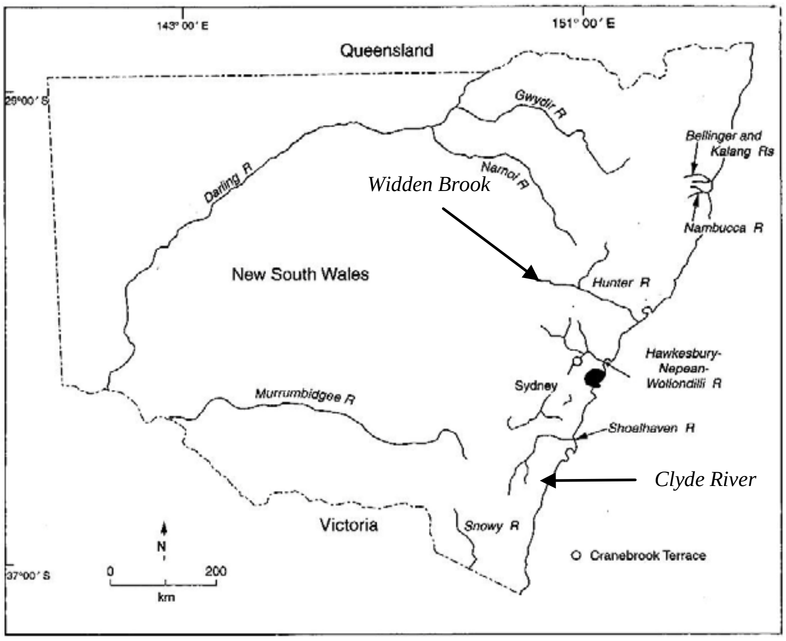


Figure 3.6: East Coast Rivers of New South Wales (adapted from Nanson et al., 2003).

Tectonic stability coupled with minimal glaciation, has meant that the rivers of south eastern Australia, have usually been starved of sediment, relative to those in other parts of the world (Nanson and Erskine, 1988). In drier times, most of the material transported by them has been the result of weathering. However, during wet periods, additional coarse sediment must have been derived from slumps and colluvium, washed from unstable hill slopes via erosion, falls or landslip (Nott et al., 2002). It is thought that sporadic and catastrophic flood events have given rise to the episodic nature of channel adjustment and the disequilibrium, which characterise the east coast rivers today and probably did so in the past (Nanson, 1986; Nanson and Erskine, 1988).

Sometimes, instead of additional sediment being deposited, it would seem that these brief, intense events may have scoured out and removed entire portions of sediment. The Nambucca Phase is a case in point, as dated samples have so far revealed little deposition from 10 - 4.5 ka, yet other proxy indicators suggest that this was probably a time of enhanced flow regime in southeastern Australia (Cohen and Nanson, 2007). A possible compounding factor may be that enhanced rainfall stabilised the vegetation and consolidated the soil, resulting in considerable run off, with increased river discharges but low sediment yields. This sediment free water was able to scour the valleys clean and leave a relative absence of alluvial fills as evidence of flow enhancement (Dodson, 1987; Cohen and Nanson, 2007).

This period was also a time along Australia’s east coast, where sea level changes influenced river deposition in low land areas. Rising sea levels facilitated deposition near estuary reaches and falling levels scoured the sediment out again (Murray-Wallace, 2002). For this reason, all the aforementioned studies have examined valleys upstream of the influence of base level changes.

3.12 Summary of Key Points

1. While there have been a range of studies into different aspects of Kangaroo Valley and the surrounding region, the changing form and processes of the Kangaroo River throughout the late Quaternary have been overlooked.
2. Terrace formation depends on a wide range of variables and a chronological record of past changes can be preserved only if certain conditions are met.
3. The flow regimes of the rivers of south east Australia show a consistent time pattern of wet and dry periods reflecting late Quaternary climate changes.

CHAPTER 4
METHODS AND RESULTS

4.1 Introduction

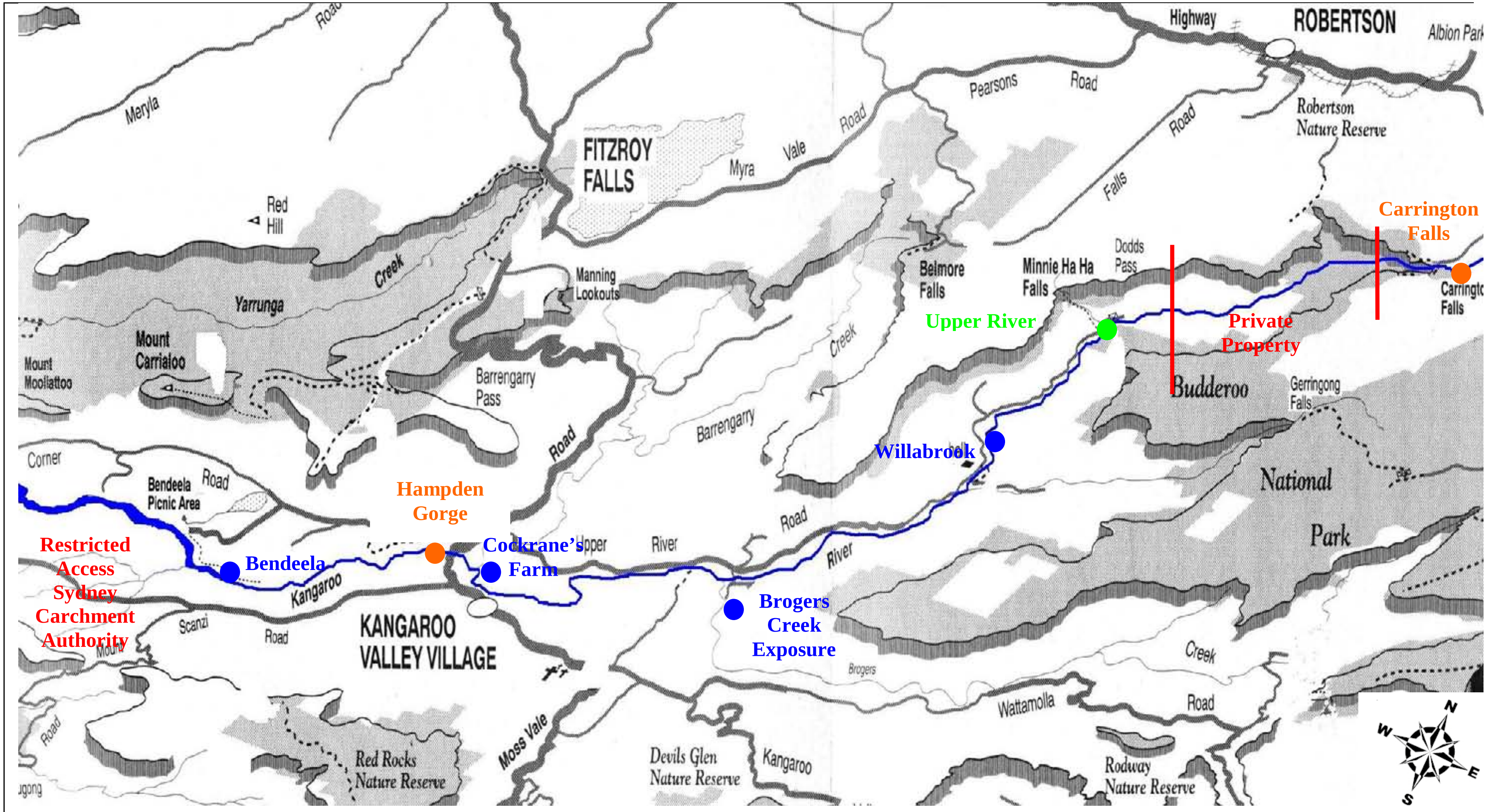
This chapter presents all the methods used in this study together with the obtained results. Each section of the chapter is devoted to one aspect of the research and includes a summary of the relevant laboratory and/or field methods as well as the results. The chapter concludes with a summary table of the results to facilitate comparison between sites.

4.2 Location Selection

The extreme ends of Kangaroo River could not be included in this study. The gorge immediately below Carrington Falls was inaccessible, because the walking track to this area had been closed by National Parks and Wildlife while access from Upper River to the gorge was barred due to private landownership. The bottom section of the river from Bendeela to Tallowa Dam forms part of SCA's water catchment and the raised water level made sampling impractical. The schematic map of Kangaroo Valley (Figure 4.1) shows the sites and the limits of the study area.

Five sites were chosen along the Kangaroo River between the Upper River and Bendeela. Sites were selected from field surveys and topographic maps. In some cases suitable sites had to be excluded, because landowners withheld their permission for access.

The selected sites comprised one bedrock location in the Upper River and four alluvial sites downstream. The alluvial sites were important for this study, as they provided a chronological history of Kangaroo River's past flow regimes from the changing sedimentary facies. One bedrock site was included to contrast its characteristics with the other alluvial sites. Two prominent landmarks-Carrington Falls and Hampden Gorge-are noted on the map, as these were important energy zones along the river, which were critical to an understanding of the Kangaroo River's fluvial characteristics. Finally, all site names along with their respective GPS co-ordinates are tabulated in Appendix A.



Legend: Bed Rock River Alluvial Sites Prominent Landmarks Private Property ( )

Figure 4.1: Schematic Map of Kangaroo Valley from National Parks and Wildlife Services (1992).

4.3 Upstream of Alluvial Sedimentation

4.3.1 Site 1 - Upper River

The Upper River site was located 6 km downstream from Carrington Falls. At this point, the river was confined between the walls of a near vertical narrow gorge there was no floodplain or terrace development (Figure 4.2). The flood channel was also composed of cobbles exhibiting imbrication. The edge of both the flood and main channel was surrounded by large blocks and boulders derived from the cliffs above.

Looking up the main channel.

Looking west across the channel showing no floodplain or terrace formation.

Figure 4.2: Confined River Channel.

4.4 Alluvial Sedimentation

4.4.1 Sampling

Sediment samples were taken from the alluvial reaches of the river with the collection method being determined by the individual site characteristics. At a vertical exposure on Brogers Creek, a section of face was cleared of debris to reveal undisturbed sediment and a series of sediment samples was then collected. Finally, the depth and stratigraphy of each terrace was measured to complete a detailed analysis of the sedimentary unit (Figure 4.3).

Figure 4.3: Exposure Sampling at Brogers Creek

At the remaining alluvial sites, an outcrop was not available, so vertical holes were augered. Stratigraphic units were recorded down each hole in the field. A small amount of sediment was bagged at 0.5 m intervals or more regularly if a distinct horizon change occurred and this material was later analysed.

Note: this section deals only with the field observations and hole numbers decrease moving away from the channel.

4.4.2 Site 2-Willabrook

Willabrook was composed of a small island with the current channel on the eastern side, a series of billabongs along the western side and a small dry channel running through the middle (Figure 4.4). This site was located 4 km below the Upper River site.

Cobbles on the edge of the billabongs.

Looking down the main channel.

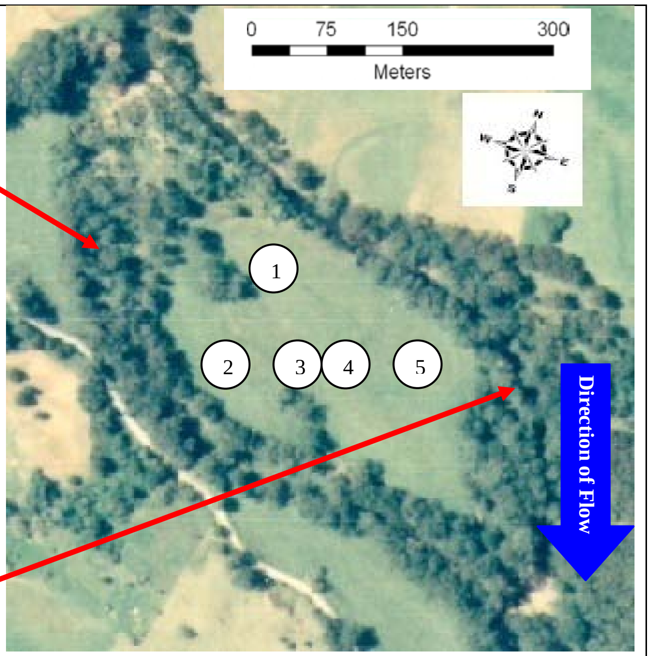


Figure 4.4: Looking Up River.
Aerial image showing position of holes.

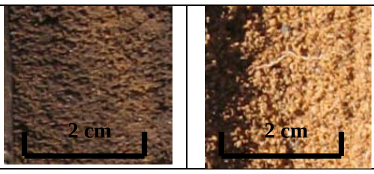


Figure 4.5: Soil change at 0.5 m

A poorly formed brown, sandy top soil was present in the first 0.5 m of each hole. A distinct change to medium non-cohesive, orange sand occurred below this (Figure 4.5). Each hole then continued to variable depths.

Holes 3, 4 and 5 were all composed of mainly fine non-cohesive, orange sandy sediment, along with a steady stream of charcoal fragments interspersed with lenses of pebbles between 3 – 5 mm along the b-axis. Hole 1 also followed this pattern but had a slight increase in pebble content.

The only real exception was Hole 2, in which the first metre was composed of relatively soft, fine, sandy sediment with more charcoal fragments and a small band of mottling at a depth of approximately 1.15 m.

4.4.3 Site 3-Brogers Creek Exposure

This site was an exposure, where Brogers Creek has cut a nearly vertical section through the Kangaroo River floodplain and adjacent terraces. This site was located 5 km downstream from Willabrook and was included, as it contained one of the best alluvial exposures along the valley (Figure 4.6).

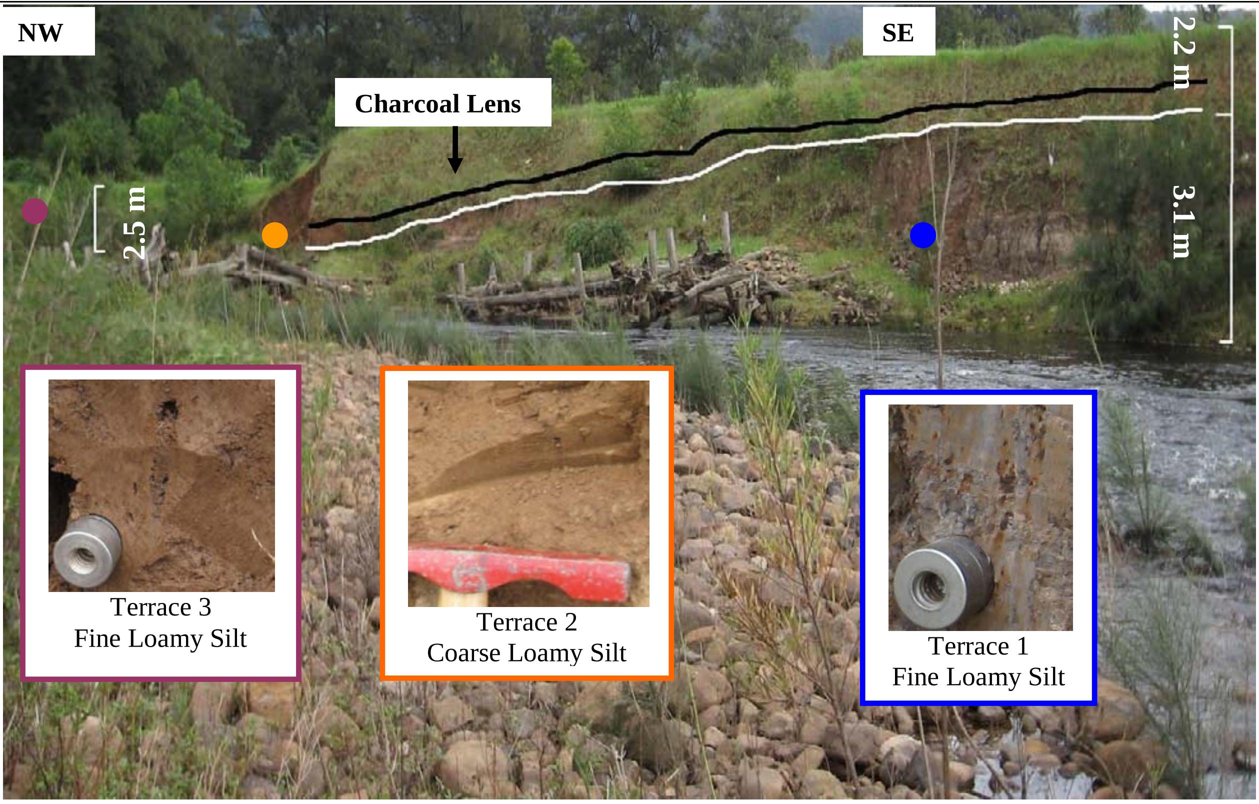


Figure 4.6: Brogers Creek exposure plus inset pictures of the three distinct soil colours which characterise each terrace.

All terraces at the Brogers Creek exposure had ~ 0.4 - 0.5 m of top soil, in the form of a distinct horizon. Below this there was a marked colour change, which was different for each terrace. Terrace 1 consisted of ~ 2.2 m of orange, loamy sand with a poorly defined charcoal lens approximately half way through it. Below the orange layer, there was a change to a largely hard, fine silty unit. This unit was distinctly mottled from top to bottom with roughly equal amounts of orange, grey and brown. There were also some black fragments, which increased in volume towards the bottom of the unit. Some smudged, thereby suggesting charcoal, whilst others did not, suggesting manganese. The bottom of the unit rested upon partly weathered cobbles of ~ 0.15 m in size.

Terrace 2 was an fine orange, loamy sand with consistent colour from top to bottom. There was a charcoal lens located ~ 4.2 m from the top and this was been part of the lens observed in the top metre of Terrace 1. The bottom metre of the unit was significantly softer and easier to remove, indicated by an increase in sand content. Again this unit sat upon cobbles of around 0.15 m in size.

Terrace 3 was homogenous from top to bottom and was composed of a brown/purple sediment with a small amount of grey mottling. It was a fine, loamy silt containing a steady stream of charcoal fragments.

4.4.4 Site 4-Cockrane's Farm

Cockrane's Farm was located 7 km downstream from the Brogers Creek exposure and 1 km upstream from the Hampden Bridge. It consisted of a large extensive flood plain ~ 1 km wide. Five auger holes were evenly spaced across the floodplain (Figure 4.7).

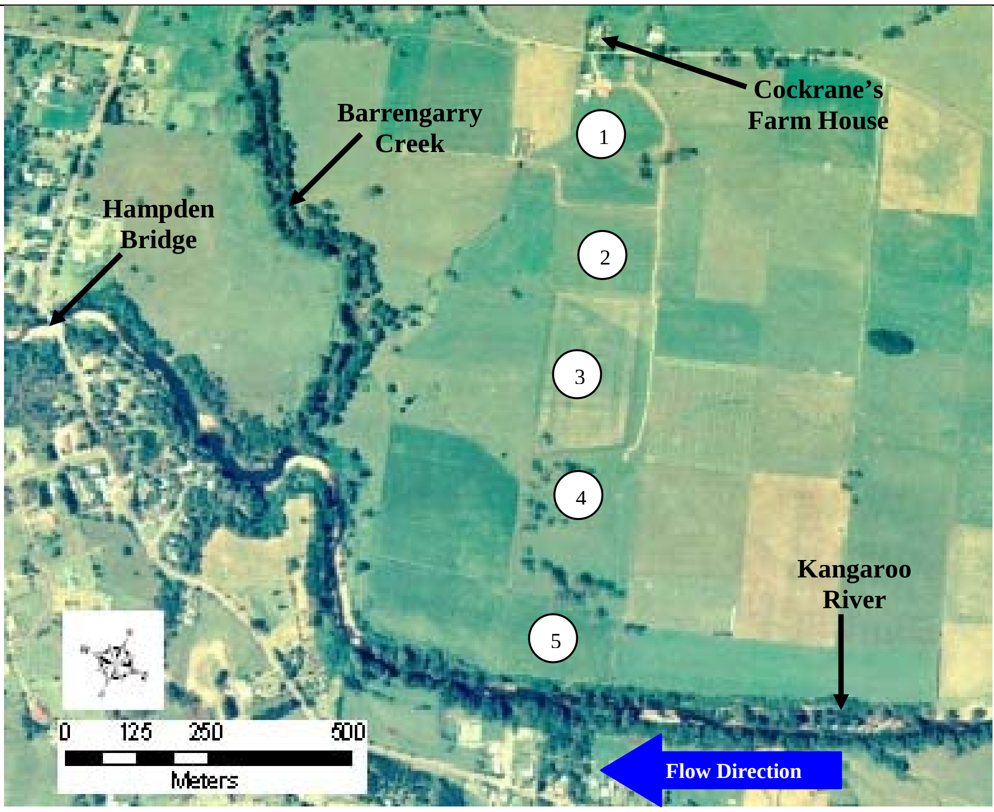


Figure 4.7: Aerial picture of Cockrane's Farm with the auger hole positions.

Sediment collected from each auger hole showed very similar physical characteristics. However, the colour of the sediment changed moving vertically downwards in each hole. The first 0.5 m was top soil, which varied in moisture content and colour from dry and pale, grey near the river to moist and black near the farm house. The next 1 – 2 m of brown, fine, silty loam was followed by a largely mottled layer, which consisted of roughly equal amounts of grey, yellow and orange (Figure 4.8). These sediment colours and textures were very similar to Terraces 2 and 1 at Brogers Creek. A small, fine, sand component, increased in content down each hole. Smudging in the upper few metres of each hole, indicated the presence of small flecks of charcoal.

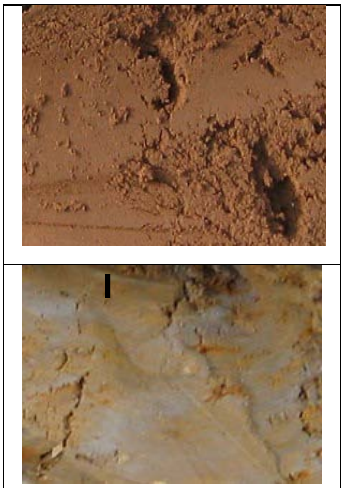


Figure 4.8: Distinct horizon change at 1 – 2 m.

With the exception of Hole 5, water was encountered. In all the remaining holes, a perched water table was located at ~ 4 m, just overlying a hard, dry clay layer (Figure 4.9). In the central three holes, there was a distinctive change from fine, loamy, silt to fine, wet sand at ~ 6 m coinciding with a lower water table, which provided a sub-artesian rise of ~ 3 m.

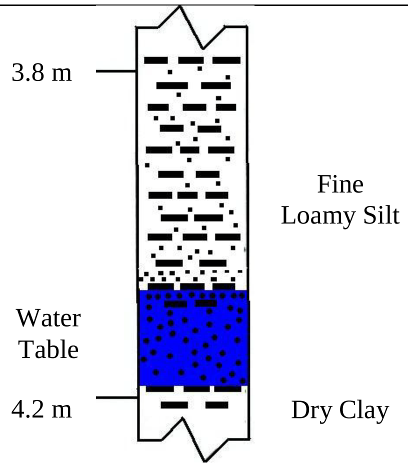


Figure 4.9: Approximate position of water table across the site.

Holes 2 to 4 continued to a depth of ~ 7 m, where the lithology changed to a sandy-silt loam, which was light, grey in colour. Holes 1 and 5 deviated from this pattern. In Hole 1, a coarse, silty loam was found between 4.9 - 5.9 m. Below this, there was a return to hard, cohesive clay. This continued down to ~ 7.2 m where rock was reached.

Finally, Hole 5 contained two coarse, silty lenses. The first was located at a depth of 5.5 - 6.0 m. The second was located between 7.7 m - 8.7 m. Between these two coarse, silty layers there was an old soil, containing rootlets (Figure 4.10). The hole was closed at ~ 8.8 m when rock was reached.

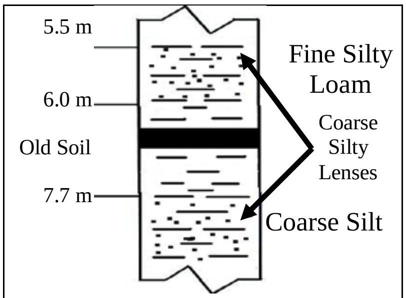


Figure 4.10: Relative location of old soil layer in Hole 1.

4.4.5 Site 5-Bendeela

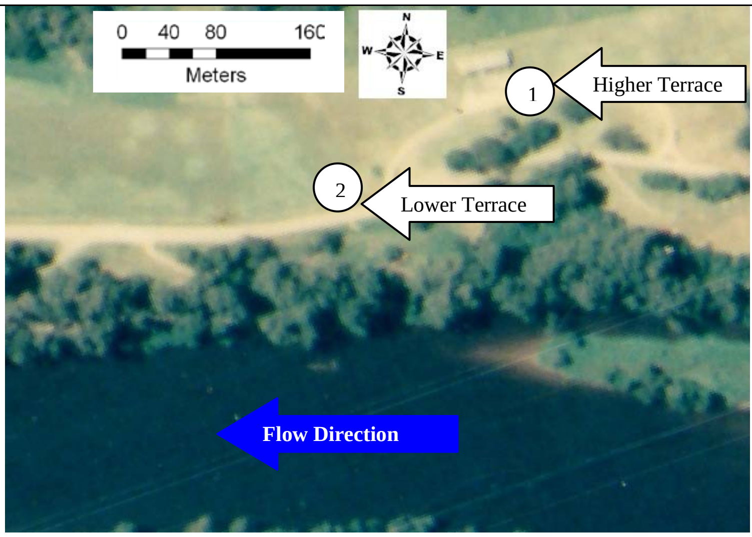


Figure 4.11: Aireal Photograph of Bendeela

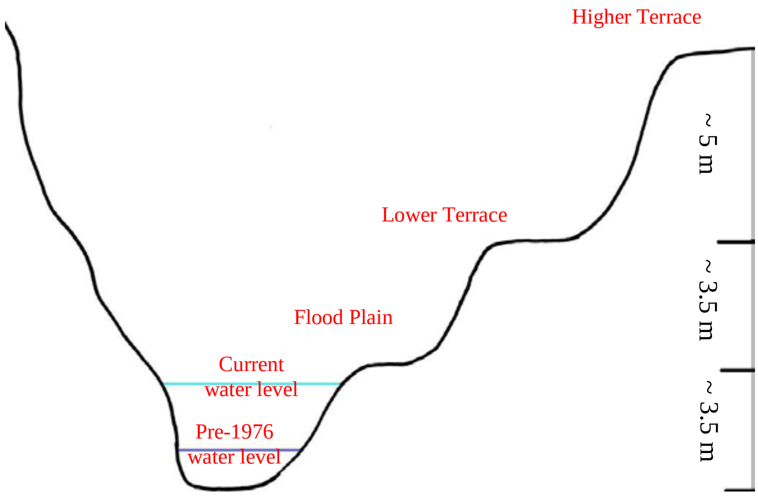


Figure 4.12: Schematic Diagram of Bendeela.

Bendeela was located 4 km down stream from Hampden Bridge and 9 km below Cockrane's Farm. Sediment has been deposited here in two terraces and a floodplain (Figure 4.11). However, the floodplain today is just above current water level due to the increase in river height, since the construction of Tallowa Dam (Figure 4.12).

Hole 1 was drilled on the top of the higher terrace. This terrace had a higher degree of top soil development, which continued to a depth of ~ 0.2 m. From 0.2 - 3.0 m, the sediment was homogenous in colour-an orange/brown (Figure 4.13). In these top few metres, there were a few charcoal fragments and the sediment was a fine, silty loam. In this terrace, there was a small degree of mottling between 3.0 - 3.4 m.

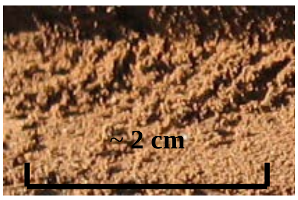


Figure 4.13: Orange sediment from Hole 2

In each sample, there were also a few red and orange sand sized particles within a fine, silt matrix. Below this depth, the sediment returned to an orange/brown silty loam and small flecks of charcoal became more prevalent. Distinct dark bands were also present from

~ 3.8 – 5.0 m, which were generally only a few centimetres thick. The hole was closed at a depth 5.7 m when rock was reached.

Hole 2, which was drilled on the lower terrace, had only about 0.1 m of top soil top soil development. Below this was yellow, fine loamy sandy sediment to ~ 1 m in depth. Below this, the sediment became dark brown and had a series of hard, loamy clay layers interspersed with softer, fine loamy sandy sediment. Within some of the finer layers, there were flecks of charcoal, but there were considerably fewer than at all the other sites.

From around the 4 m mark onwards, there was a layer of old root material. From 5.2 m, there was a distinct change to sandier sediment, which became nearly all sand at 5.5 m. The hole was closed at a depth 6.3 m when rock was reached.

4.5 Channel Sedimentology

At each site, in channel deposition was measured utilising the Wolman series. This involved selecting a rock every 1 m interval over a 100 m distance and measuring the a, b and c axis of each rock. The average size was determined from the b-axis and degree of sorting was then calculated to one standard deviation. The degree of roundness was calculated using the following formula $(bc/a^2)^{1/3}$ (Krumbein, 1941; Wolman, 1954). Field observations were made of the boulder composition and channel bed forms.

The channel bed along the length of the river is covered with boulders of variable size, rounding and sorting. The average size decreased downstream while the degree of roundness and sorting increased (Table 4.1).

Site	Average b-axis Size	Average Sorting	Average Rounding
Upper River	367.40 mm	212	0.82
Willabrook	346.46 mm	155	0.75
Brogers Creek	202.56 mm	99	0.67
Cockrane's Farm	200.16 mm	88	0.65

Table 4.1: Boulder/Cobble Sizes Obtained from each Site.

In the Upper River, the base of the main channel flowed over a succession of tessellated pavements, composed of large square blocks. This was interspersed with pool and riffle sequences composed of well rounded cobbles, showing imbrication in the downstream direction.

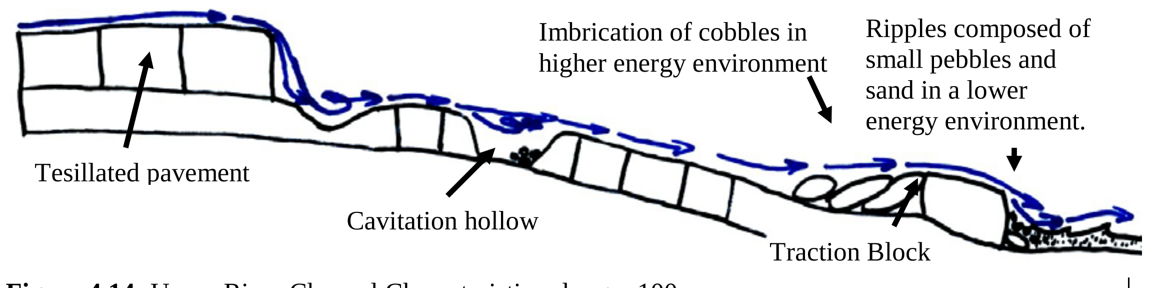


Figure 4.14: Upper River Channel Characteristics along ~ 100 m.

The coarser boulders were composed of loosely cemented sand sized particles and pebbles, so that they were easily broken down. Therefore, the finer grained boulders were more erosion resistant and became more prevalent in the lower reaches. All boulders were imbricated downstream (Figure 4.14). Note: Bendeela could not be sampled as the raised has covered the bed of the river making it inaccessible.

4.6 Grain Size

4.6.1 Method

All grainsize preparation and analysis was undertaken at ANSTO Laboratories utilising the Malvern Mastersizer 2000. The procedure involved placing approximately 1 cm^3 of sample in a 20 mL vial then adding approximately 10 mL of distilled water, placing this on a hot plate at approximately 60 °C and slowly adding 1 - 2 mL of hydrogen peroxide to remove any organics. If abundant organics are present, vigorous bubbling will occur (Lehmann, 1999). Upon completion of this reaction, 1 – 2 mL of hydrochloric acid was added to remove any trace of carbonate present, because both of these constituents do not represent depositional energy of the sample (Konert and Vandenberghe, 1997). The final step in the preparation was to allow the solution to cool before adding approximately 1 mL of sodium hexaphosphate ($Na\ (PO_4)\ _6$) and placing the samples into an ultrasonic bath for 15 minutes. This was undertaken to break clumps of clay into individual particles (Harris, 2003).

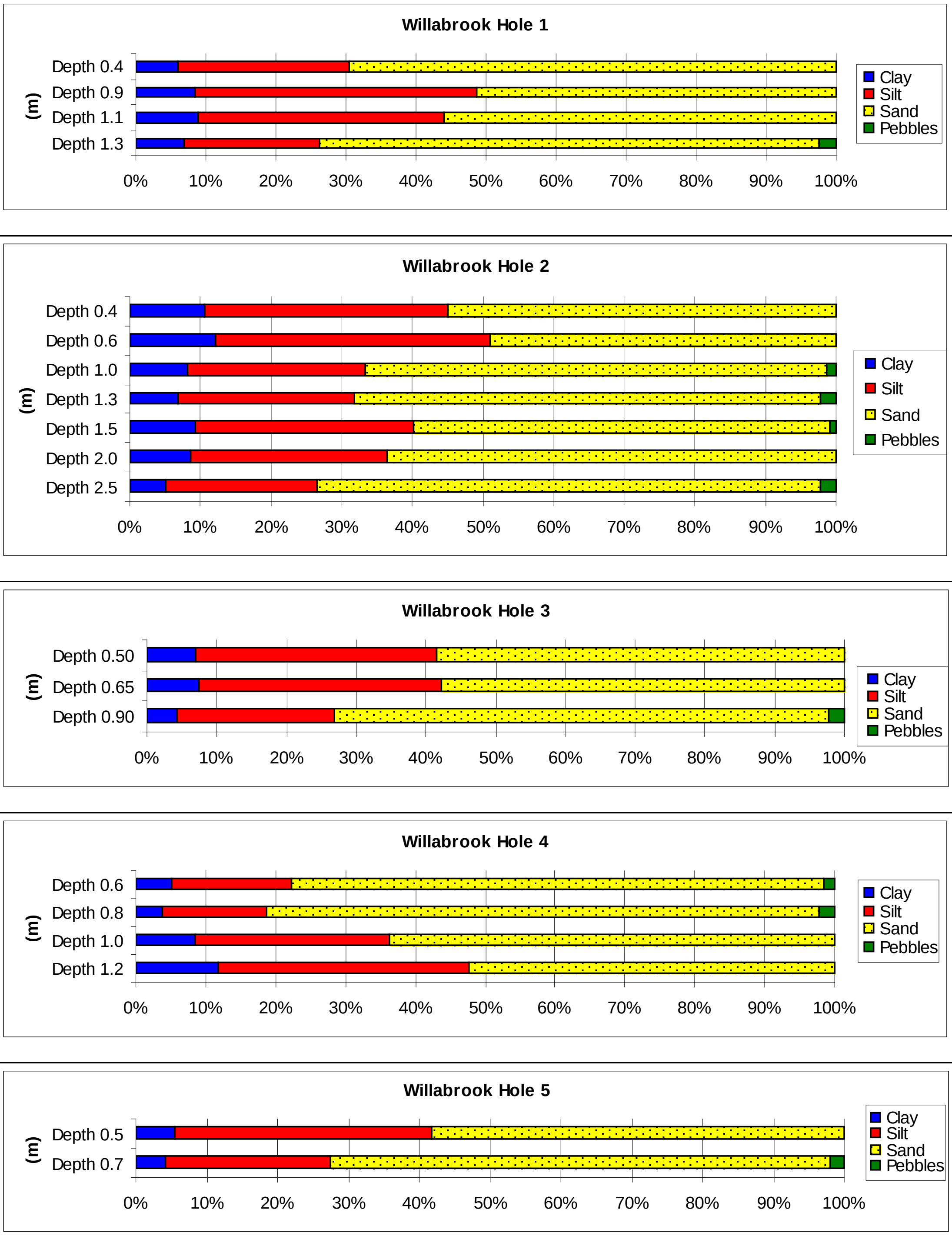
The prepared samples were then run on the Malvern Mastersizer 2000. The 20 mL vial with sample was then placed onto a magnetic stirrer to homogenise the sample. A 1 L beaker was filled with ~ 900 mL of distilled water and placed under the Malvern Mastersizer 2000. The pump was set to 2000 revolutions per minute in combination with the ultrasonic disaggregation. A background was initially run. Then a small volume of the sample slurry was added, until the obscuration was between 10 – 20 %. The sample was then automatically analysed, taking three measurements, before calculating an average. Between each sample run, the Malvern Mastersizer 2000 was flushed with clean water. For full results see Appendix B.

4.6.2 Grainsize Results for Site 2 - Willabrook

During the removal of organics, all samples had a steady stream of bubbles which was more or less equal for all sample depths, with a few exceptions. In all auger holes, the reactivity was highest in the top 0.5 - 0.6 m with very large, eruptive bubbles and froth being formed.

There was a general upward fining trend across Willabrook with around a 15 – 20 % reduction in sand content. The only exception was in Hole 4, which coarsened upwards showing an average increase of sand content of 12 %. The deeper the hole went the greater was the number of fluctuations. Hole 2 penetrated to a depth of 2.5 m and had two fluctuations, whereas the remaining holes only had one fluctuation.

The average grainsize of the sediment fluctuated between loamy sand and pebbles in the coarser lenses and silty loam in the finer lenses. The sorting of the sediment was poor to very poor. Hole 1 on the leading edge of the terrace contained the coarsest material and was the most poorly sorted (Graph 4.1).



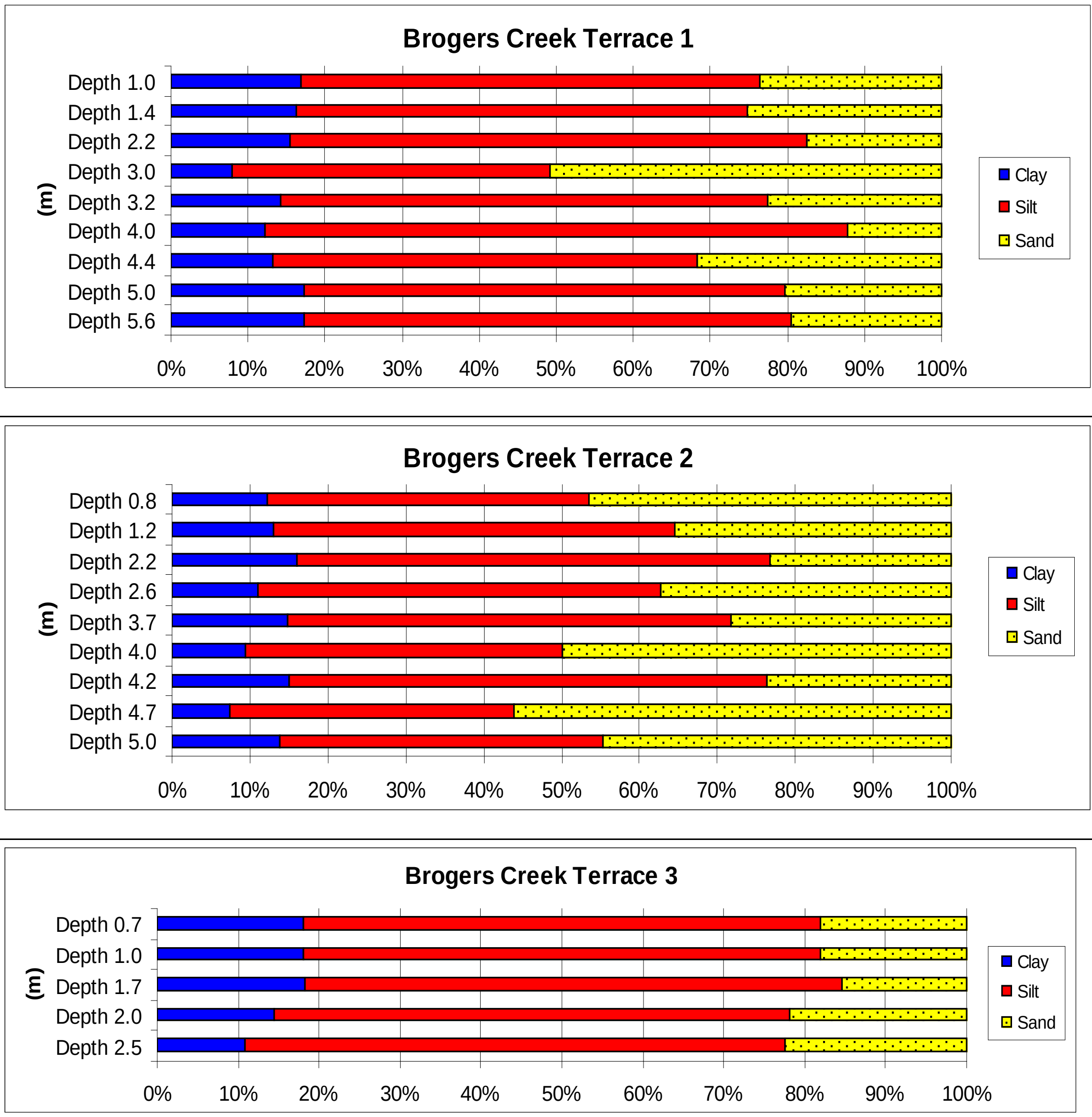
Graph 4.1: Grainsize at Willabrook.

4.6.3 Grainsize Results for Site 3 - Brogers Creek Exposure

The addition of hydrogen peroxide revealed some higher organic content at certain sample depths and in certain terraces. In Terrace 1, there was an increase in bubbling activity at ~ 3.0 m, whilst in Terrace 2, the increase occurred at ~ 3.7 - 4.2 m. In Terrace 2, this increase in activity coincided with the charcoal lens, which continued to on lap over the top few metres of Terrace 1 (Figure 4.6). Finally, in Terrace 3, there appeared to be a uniform amount of bubbling activity from the top to the bottom of the sequence. This suggested a relatively even distribution of organic material.

The grainsize results showed three distinctly different conditions. Terrace 1 showed three fluctuations, Terrace 2 had four fluctuations and Terrace 3 had two. The average percentage of sand fluctuated from 24 % in Terrace 1 to 34 % in Terrace 2 with only 19 % in Terrace 3. Terrace 3 showed an upward reduction of 10 % in sand content whilst both Terraces 2 and 1 showed only a series of random fluctuation with minimal change.

The average grainsize for Terrace 1 was silty loam with only one loamy sand lens located at ~ 3.0 m. Terrace 2 had three loamy sand lenses located at 0.8, 4.0 and from 4.7-5.0 m with the remaining lenses being silty loam. Finally terrace three was composed entirely of silty loam (Graph 4.2).



Graph 4.2: Grainsize at Brogers Creek Exposure.

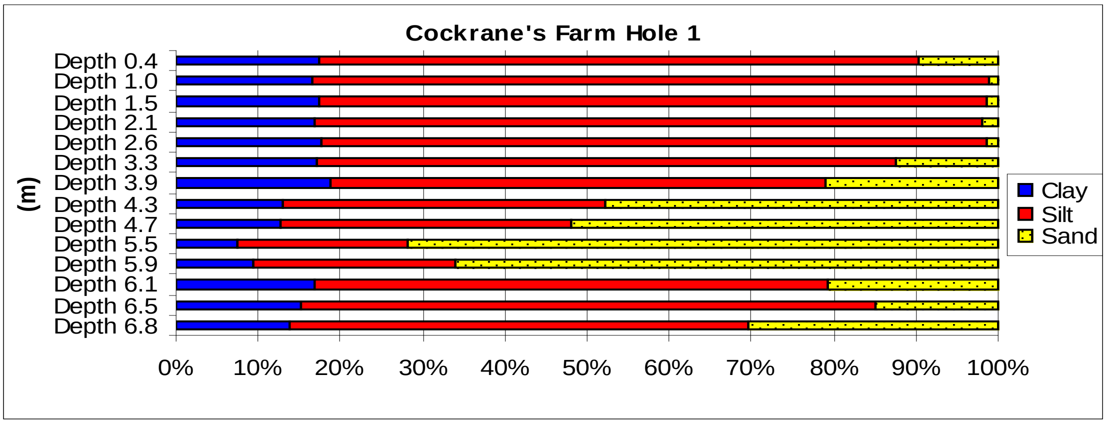
4.6.4 Grainsize Results for Site 4 - Cockrane's Farm

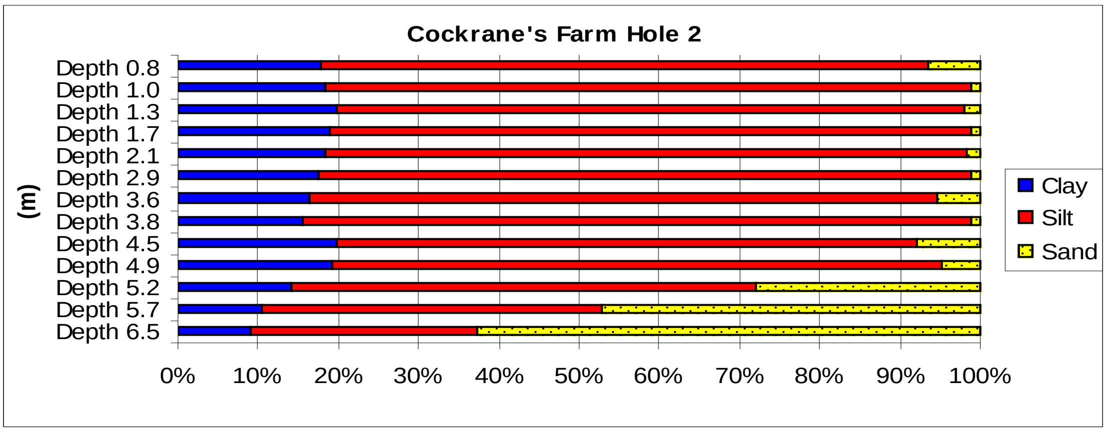
Hole	Organic Layers (m)
1	5.1 - 5.9
2	5.9-6.5
3	5.0, 6.7 - 7.0
4	4.3, 6.5-6.8
5	4.2, 6.7 - 6.9

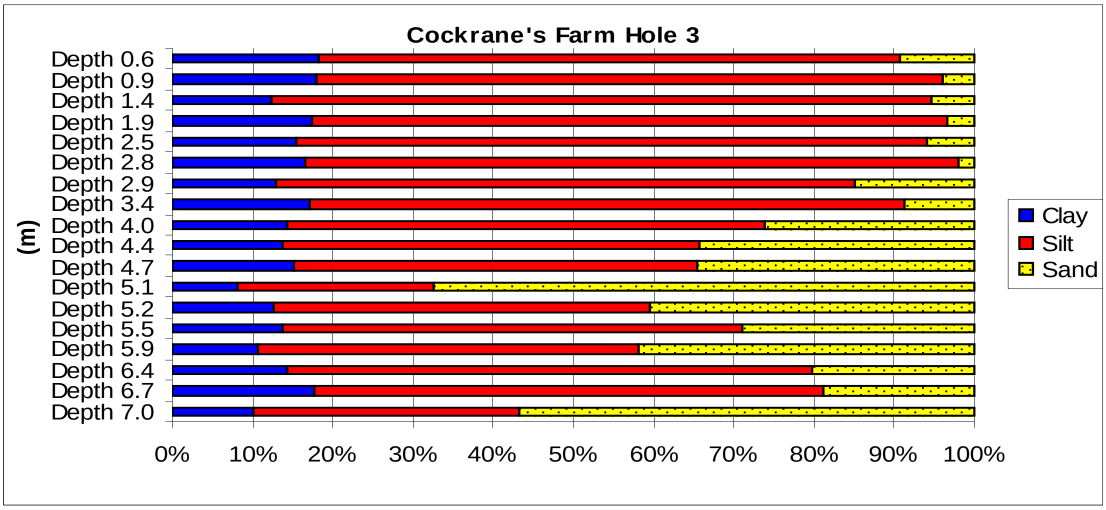
Table 4.2: Depths of Increased Organic Activity

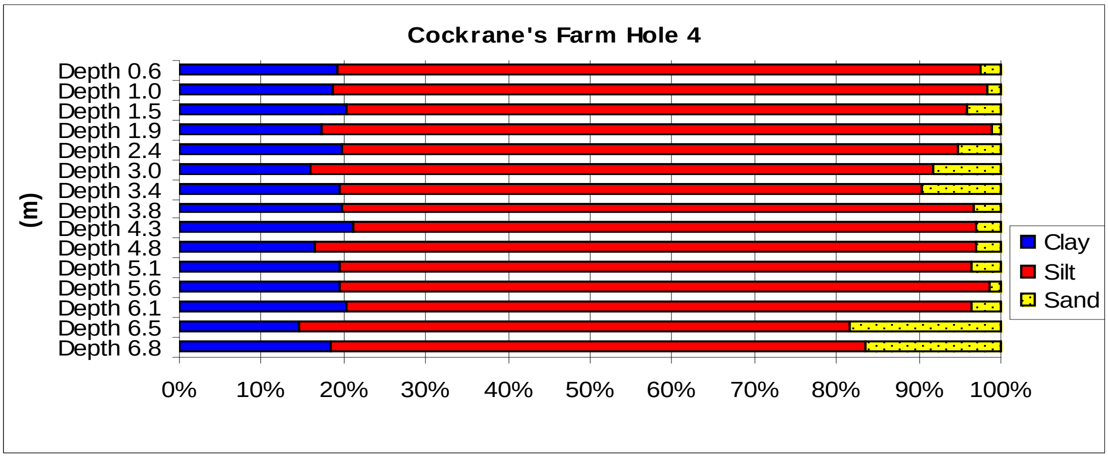
The addition of hydrogen peroxide revealed some higher organic content, which were located just above or within the coarser material (Table 4.3). Each hole showed variable degrees of fluctuations, ranging between three and six per hole with Hole 5 showing the most intense activity. There was a general reduction in sand content of ~ 8 % moving away from the current river channel and each hole showed a fining upward sequence.

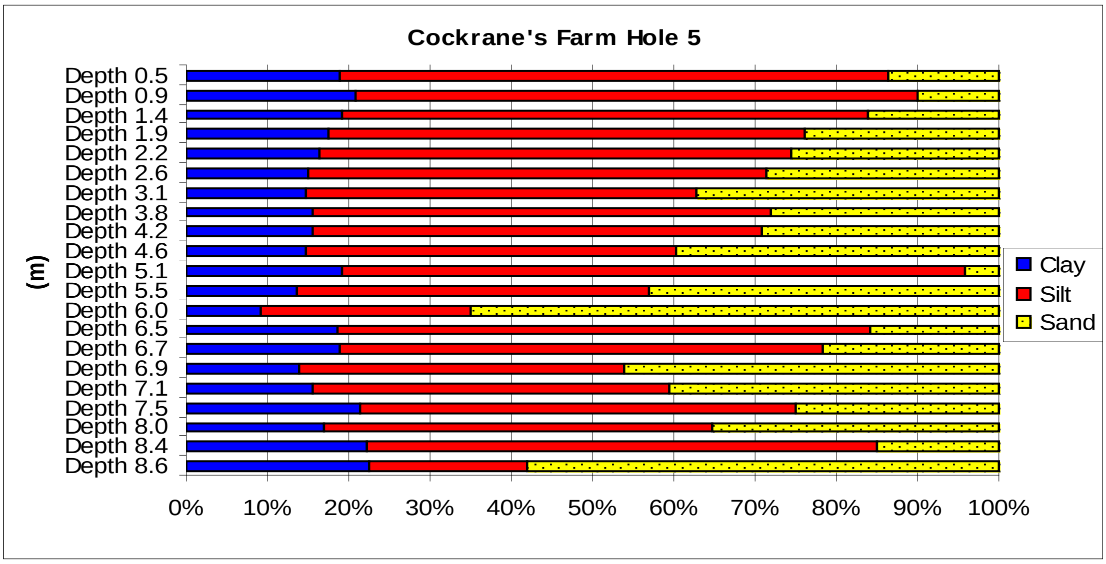
The average grainsize for Hole 1 was silty loam with a single lens of loamy sand between the depths of 4.3 – 5.9 m. Hole 2 was mostly silty loam with a loamy sand lens between 5.7 - 6.5 m. Hole 3 had three sandy loams between 5.1 - 5.2, 5.9 and 7.0 m with the remainder being silty loam. Hole 4 was entirely silty loam. Finally, Hole 5 had four sandy loams at the depths of 4.6, 5.5 – 6.0, 6.9 – 7.1 and 8.6 m with the reminder being a silty loam. Sorting improves moving away from the current channel (Graph 4.3).











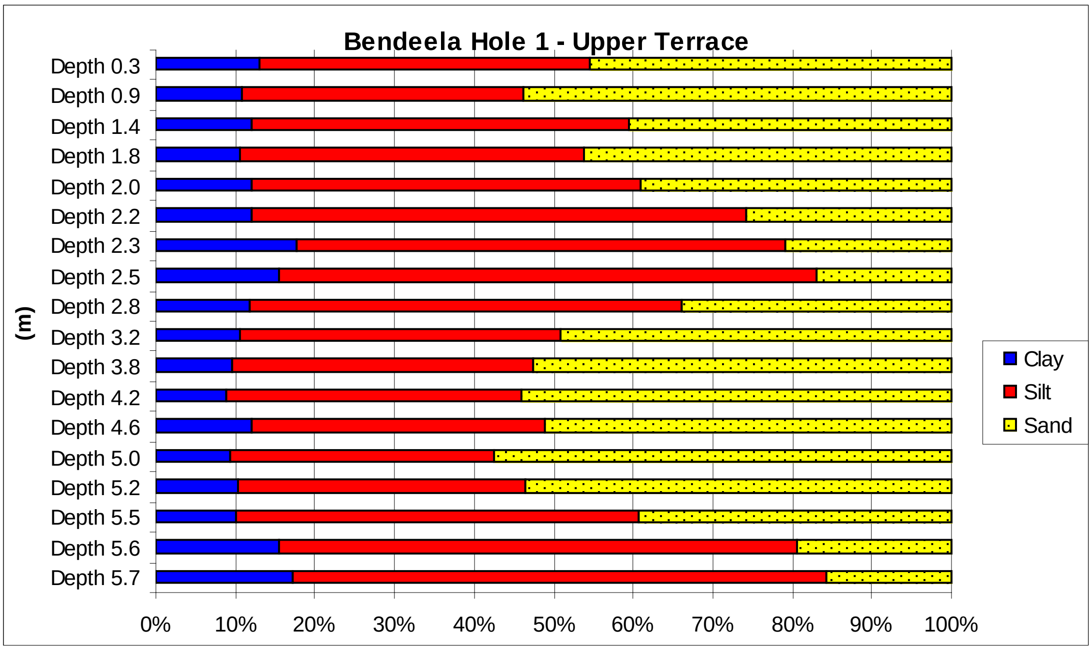
Graph 4.3: Grainsize at Cockrane's Farm.

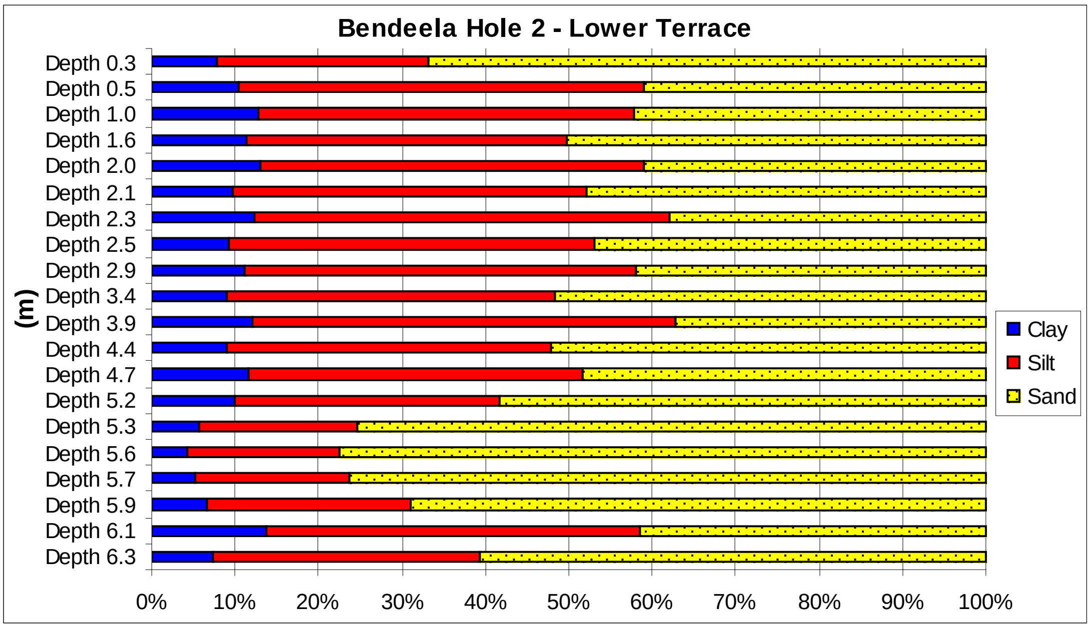
4.6.5 Grainsize Results for Site 5 - Bendeela

At Bendeela, both auger holes showed distinct differences in their reactivity to hydrogen peroxide. In Hole 1 all of the samples were quite reactive, with the exception of 4.7 - 5.0 m. In Hole 2, there were two distinct zones of enhanced reactivity- 0.5 - 2.0 m and 4.7 - 5.5 m. Indeed the reaction here looked similar in intensity to those at Willabrook.

The grainsize results showed two distinct conditions. Hole 1 had three fluctuations with no distinct upward fining. Hole 2 had six fluctuations with an upward fining sequence, with the percentage of sand reducing by ~ 19 %. The average percentage of sand was~ 14% less in Hole 1 than in Hole 2.

The average grainsize in both holes was loamy sand, interspersed with silty loam. In Hole 1 there were two prominent lenses located between 2.0 – 2.8 m and 5.5 – 5.7 m whilst in Hole 2 there were three small lenses located at 2.0, 2.3 and 3.9 m in depth. Sorting was poor across both holes (Graph 4.4).





Graph 4.4: Grainsize at Bendeela.

4.7 Vegetation

 Upper River	Rainforest vegetation such as Lilly Pilly *(Acmena smithii)* and Coachwood *(Ceratopetalum apetalum)* were prevalent. Casuarinas *(Casuarina cunninghamiana)* occasionally interspersed.
 Willabrook	The terraces have been cleared to provide farming pastures. Natural vegetation is confined to the riparian corridors consisting mainly of Casuarinas *(Casuarina cunninghamiana)* interspersed with occasional Coachwood *(Ceratopetalum apetalum)*.
 Brogers Creek	In the lower reaches at Brogers Creek and Cockrane's Farm, invasive weeds such as Shrub verbena *(Lantana camara)* and Farmers Friend *(Biddens pilosa)* intermingle with Casuarinas *(Casuarina cunninghamiana)* and tea trees *(Leptospermum myrtaceae)*.
 Bendeela	At Bendeela eucalyptus species such as White Stringy Bark *(Eucalyptus globoidea)* predominate along the steep, dry slopes along with tea tree *(Leptospermum myrtaceae)*. Casuarinas *(Casuarina cunninghamiana)* become less prevalent.

Table 4.3: Vegetation Communities along the river.

4.8 Transects

A transection was performed at each site to determine channel geometry, terrace surface and a gradient along approximately 100 metres of the river. the survey at each site was carried out at each site using a dumpy and staff. When LiDAR became available, this was used to confirm the results at Cockrane's Farm and the Brogers Creek exposure. At all of the alluvial sites, the position of the holes was marked and the sedimentary logs were added.

Note: According to Buol's soils classification (1973), the grainsize results for Brogers Creek, Cockrane's Farm and Bendeela were all 'silty loam'. However, to show the fluctuations in grainsize percentages in each of the alluvial site transects, 60 % was set as a dividing line. Sediment with 40 % or greater sand content was labelled as 'loamy sand' whilst sediment containing less than 40 % sand, was labelled as 'silty loam'.
All transects, were tied to the Australian Height Datum (AHD) – equivalent to mean height above sea level.

4.8.1 Site 1 - Upper River

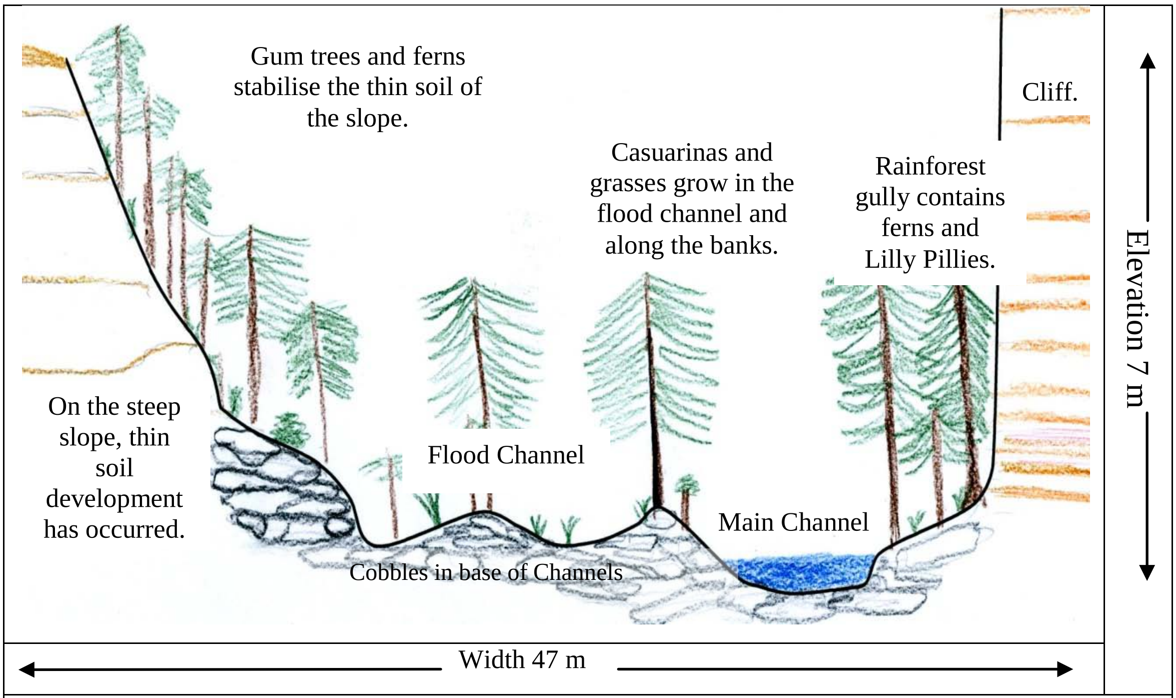


Figure 4.15: Upper River Transect.

4.8.2 Site 2 - Willabrook

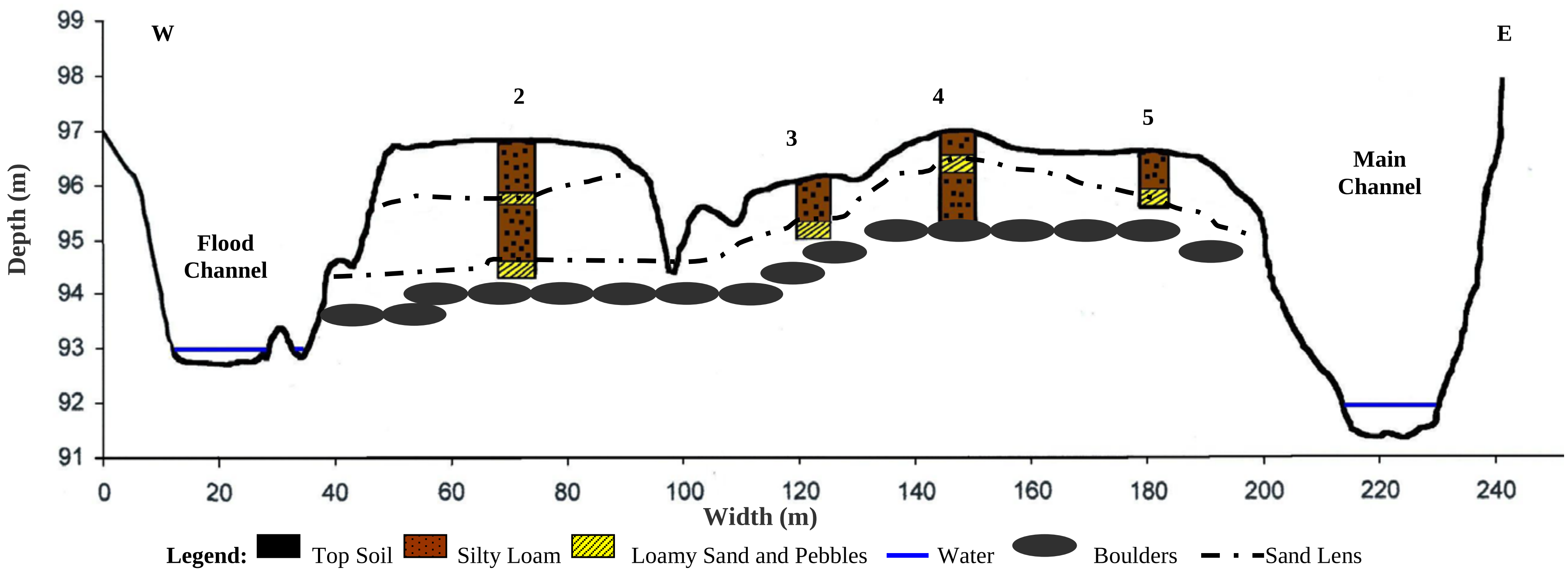


Figure 4.16: Willabrook Transect.

4.8.3 Site 3 - The Brogers Creek Exposure

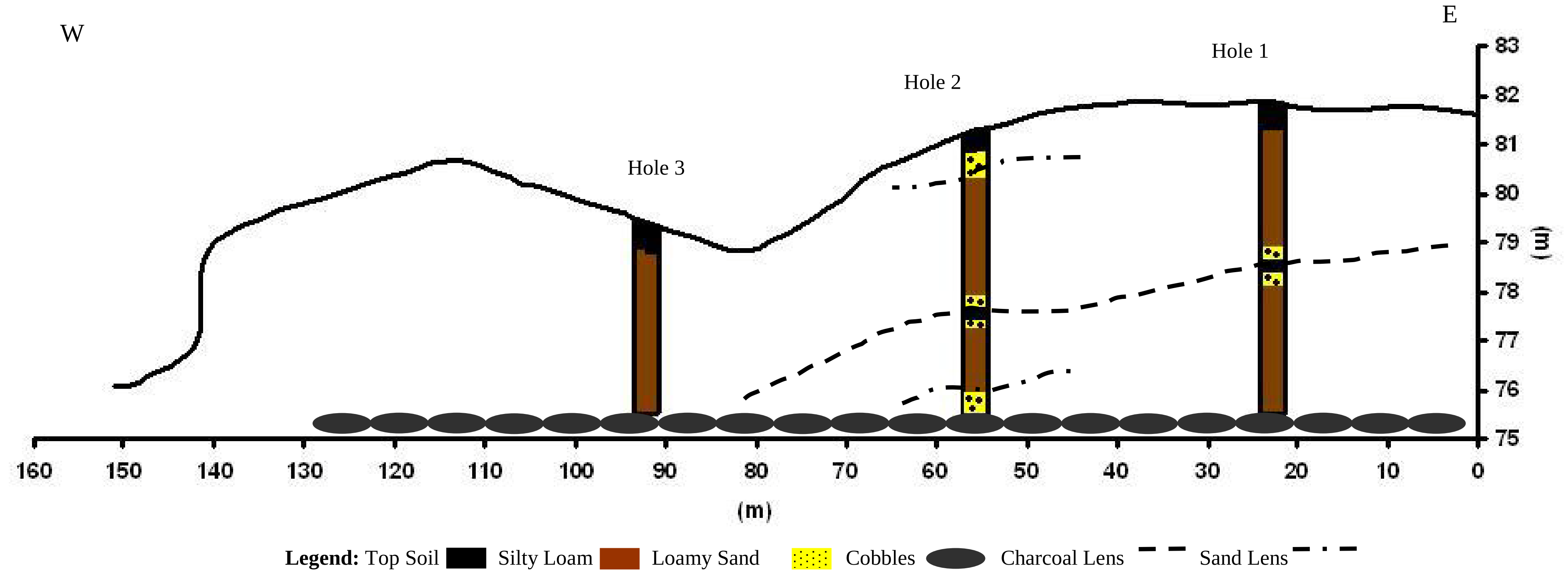


Figure 4.17: Brogers Creek Transect.

4.8.4 Site 4 - Cockrane's Farm

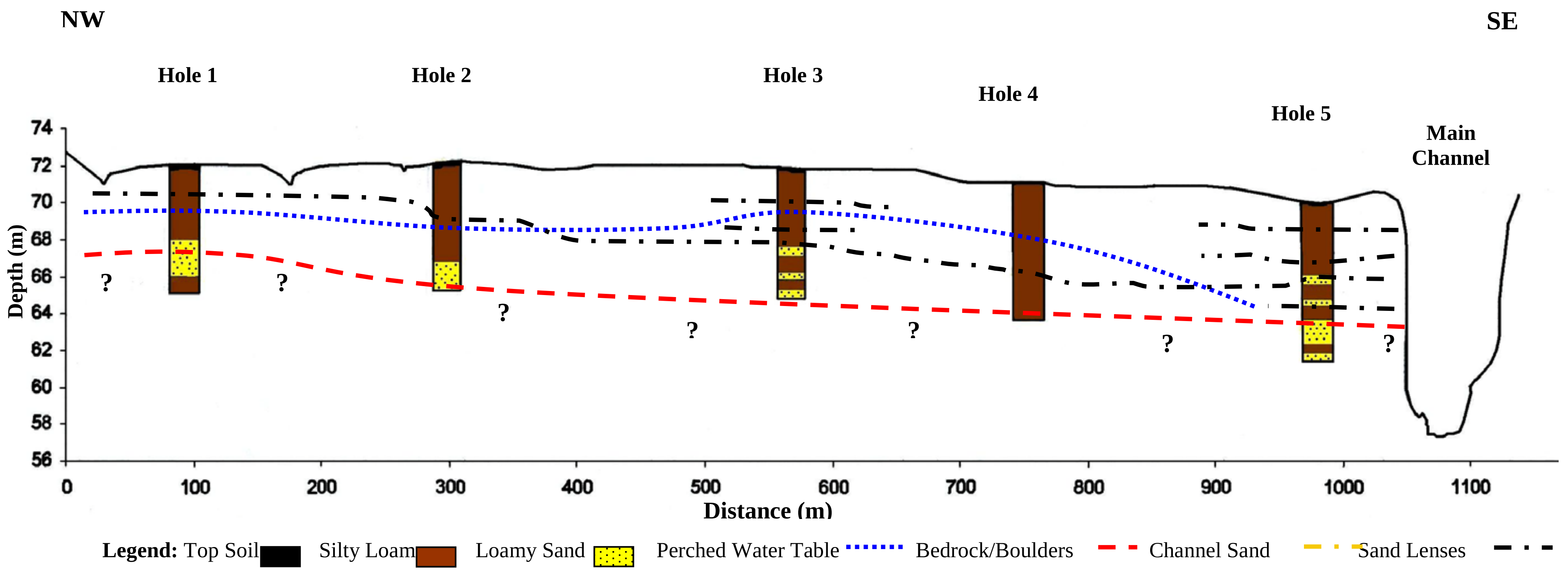


Figure 4.18: Cockrane's Farm Transect.

4.8.5 Site 5 - Bendeela

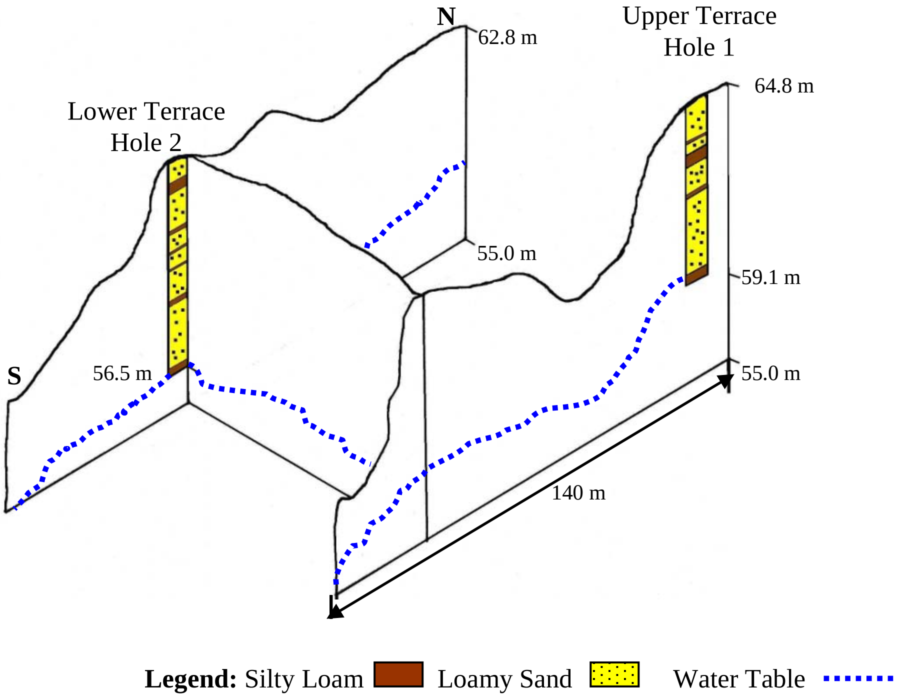


Figure 4.19: 3D Cross section of Bendeela derived from the two transects completed in the field.

4.8.6 Comparison of Site Topography

At both Upper River and Willabrook, there was a main channel and a flood channel. At Upper River the channels were separated by an undulating boulder surface, which was ~ 2 m in elevation above the channel surface. However, At Willabrook, main and a flood channel were now separated by an undulating floodplain of ~ 300m width at its widest point and a maximum surface elevation of ~ 9 m above the channel surface. At the next two sites of Brogers Creek and Cockrane's Farm, there was no longer a distinct flood channel and they were now composed of a series of gentle sloping terraces. The Brogers Creek terraces were 5.2 m in maximum elevation above the channel surface and ~ 450 m wide whilst at Cockrane's Farm, they were ~ 15 m above the channel surface and ~ 1000m wide. Finally, at Bendeela, the terraces showed a step wise rise from the current water surface of 7.2 m on the lower terrace to ~ 9.2 m on the higher terrace but the terrace width was only~200m.

4.9 X-Ray Diffration (XRD)

4.9.1 Method

An analysis of the minerals present provides useful information about whether minerals have been derived directly from parent material in the surrounding catchment or whether they are the result of subsequent chemical weathering (McKenzie et al., 2004).

X-ray diffraction uses Bragg's law to provide information about the crystal lattice in the sediment under analysis (Young and Freedman, 2008). It identifies the percentage composition of minerals present. Samples need to be in a powder form so that the crystalline domains are randomly oriented (Mitra, 1989; Atkins and Jones, 2004). In this way, the distinct mineralogy of the sediment can be identified.

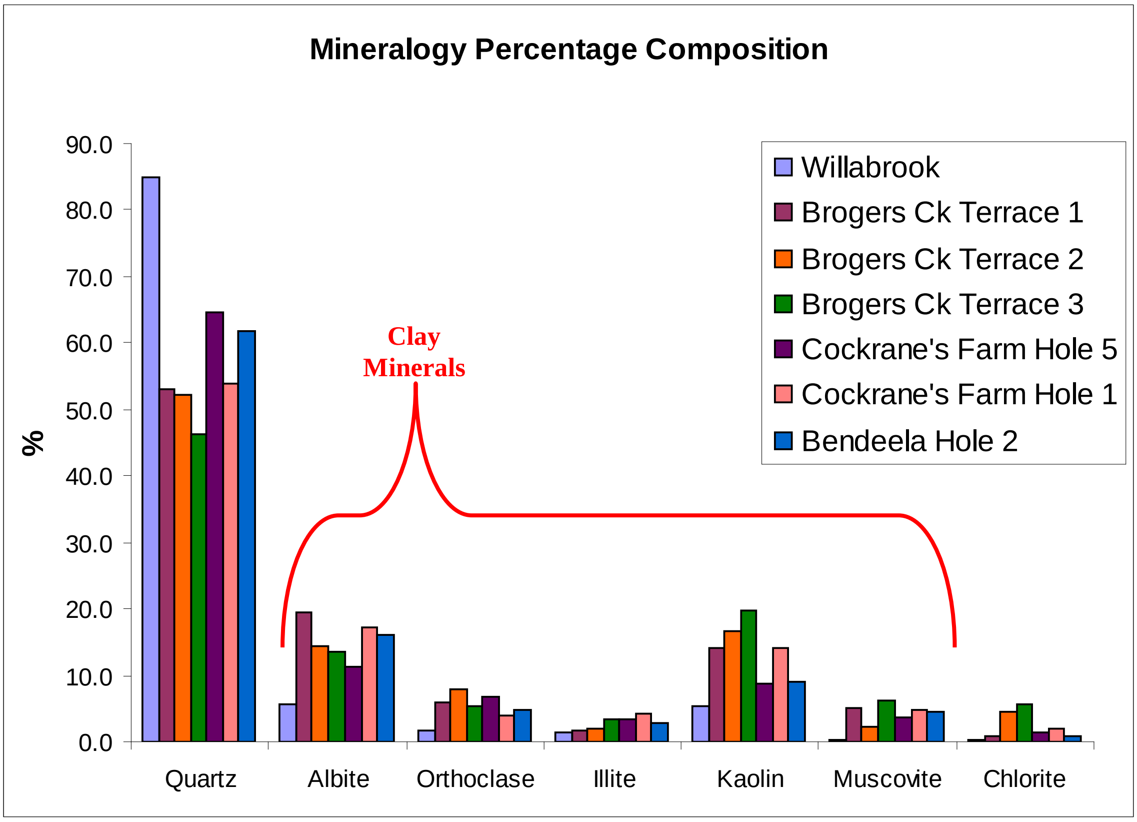
From selected auger holes at each alluvial site, three to four samples were chosen. A few grams of each sample were dried and crushed. The powdered sample was placed into a cassette and the X-ray beam was moved through a series of angles to determine the crystal structure and hence the mineral composition of the sample. The result was analysed at University of Wollongong Laboratories using CSIRO software.

Note: Full results are located in Appendix C.

4.9.2 XRD Results

The results from XRD (Graph 4.5) showed that a very similar set of minerals were present along the downstream channel and across the terraces. By far the most prevalent mineral was quartz (average of 75 %), with the percentage increasing down each hole. Therefore, the remaining minerals showed a decreasing percentage with depth.

Kaolin and albite were the next most prevalent minerals with around 10 – 20 % on average. All other minerals, namely orthoclase, illite muscovite and chlorite, were less than 10 %.



Graph 4.5: Mineralogy.

4.10 Mapping
4.10.1 Methods

In the past geologists had to rely on topographical maps and their own fieldwork. While these tools remain an essential part of any study, Geographic Informations Systems are now available, which can increase the accuracy, speed and hence the scope of a research project (Longley et al., 2005).

LiDAR surfaces collect ground data with a small diameter laser beam, which provides excellent horizontal resolution of one to two metres and a high degree of vertical accuracy. This makes them ideal for research into historic flood events and hydrological prediction (Teng and Vaze, 2010).

A Geographic Information System (GIS) called ArcGIS was used to analyse the map data. The LiDAR data was already rectified and had also been ground corrected to remove the effect of vegetation and thus provide only the ground surface elevation. Arc Tool Box was used to convert the data points into a Triangulated Irregular Network (TIN) surface. From here the data was then converted into a raster format with a cell size of 0.5 m to provide a surface, upon which a series of analyses could be performed (Longley et al., 2005). Channel morphology and terrace width were the primary focus of analysis and the LiDAR surface also showed some areas of interest, which warranted further investigation.

Unfortunately, the LiDAR only provided only provided 32 % of the study area and to cover the remaining area, a Digital Elevation Model (DEM) was also produced. This was undertaken by the Spatial Analysis Laboratories at Wollongong University and was derived from the topographic maps of the river. While its accuracy was lower than the LiDAR, it enabled a long river profile and gradient to be created.

The other problem, for which no alternative solution was available, was the absence of bathymetry in either LiDAR or DEM. This meant that modelling of flood regimes could not be carried out. It also meant that the channel gradients obtained from the DEM were only to the water surface from the original topographic map.

4.10.2 Results

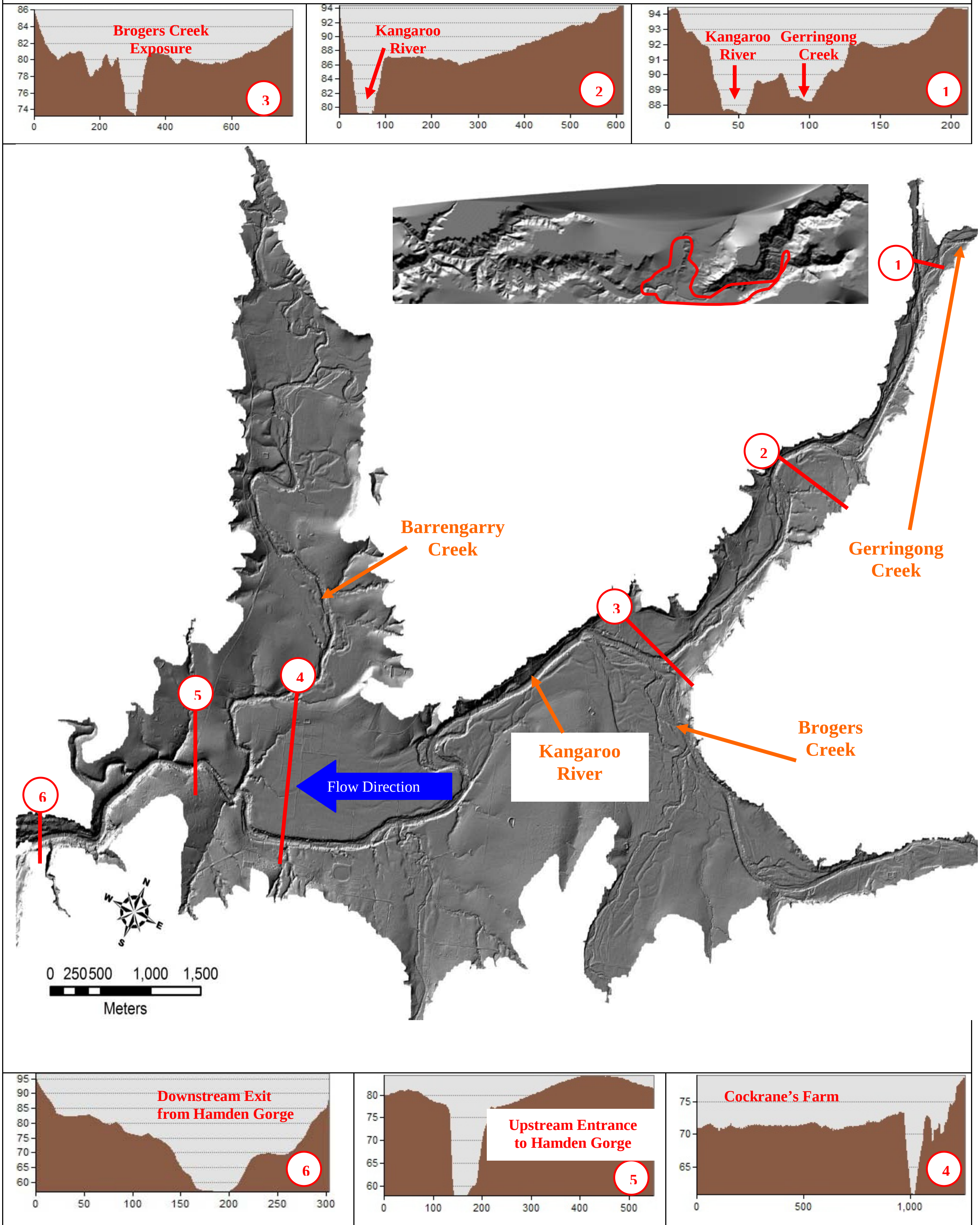


Figure 4.20: LiDAR Surface. DEM Inset map shows the region which is covered by the LiDAR.

Note: all cross sections are in metres.

Combining the LiDAR data with the ground surveys provided detailed information about how the channel geometry and floodplain width changed moving downstream. Cross sectional profiles were calculated at bank full capacity whilst a Mannings n value was estimated.

Site	Upper River	Willabrook	Intermediate Point	Brogers Creek	Cockrane's Farm	Hampden Gorge Entrance	Hampden Gorge Exit
Channel Width (m)	40	60	84	87	110	75	89
Channel Depth (m)	2.2	6.6	5.4	4.4	9.4	12.5	3.4
Gradient	0.0100	0.0080	0.0065	0.004	0.0015	0.0015	0.0015
Area (m^2)	88.0	396.4	453.6	382.8	1034.0	937.5	302.6
Shear Stress (N/m^2)	194.02	423.66	304.45	194.26	117.88	137.66	46.38
Discharge (m^3/s)	154.28	1819.19	1730.70	1493.88	2675.99	2690.58	420.50
Mannings n	0.09	0.06	0.06	0.06	0.06	0.06	0.06
Floodplain Width (m)	0	300	415	450	1000	0	480
Floodplain/Channel Width	N/A	1 : 5.0	1 : 4.9	1 : 5.2	1 : 9	N/A	1 : 5.4

Table 4.4: Channel Geometry: Figures from LiDAR except Upper River and Willabrook, which used ground surveys.

The gradient reduced from the Upper River to the Brogers Creek exposure, before stabilising at 0.0015 m/m from Cockrane's Farm through to Bendeela. Generally the channel geometry results showed an increase in capacity from Willabrook to Cockrane's Farm, before reducing slightly at Hampden Gorge and then increasing again at the exit from the gorge. The sheer stress showed a general decline to Cockrane's Farm, before increasing at the entrance to Hampden Gorge and then reducing at its exit (Table 4.4).

4.11 Radiocarbon Dating

4.11.1 Background

Carbon 14 (^{14}C) was one of the earliest radiometric techniques to be developed. Three isotopes of carbon exist-^{12}C, ^{13}C and ^{14}C-with the latter being unstable and breaking down over successive half lives, which have been calculated to be 5730 a. Carbon is taken up by living organisms and so the ratio of ^{14}C in the environment and the organism remains constant until it dies, after which ^{14}C begins to break down. By comparing the ^{14}C in the organism to that of the current environment, an estimate of its age can be ascertained. The pioneering work of Willard Libby has led to ^{14}C being applied to many applications such as bone, charcoal soil and shell. It is useful in dating Quaternary events due to its age range which is 500 a. to 50,000 a. (Walker, 2005).

However, there are a number of issues which need to be considered. One problem is the reliability of the dates. A key assumption underlying radio carbon dating is that radioactive decay has been constant, since the material was deposited. However, climatic fluctuations cause variations in the decay rate (ANSTO, 2010), so that the dates can contain errors (Walker, 2005).

Some specific problems also arise in dating fluvial sediment. River sediment often contains very little datable material (Chandra et al., 2007; Page et al., 2007) and even if it is present, carbon dating assumes that this material dies at the same time as the sediment was deposited. This can be difficult to establish with any degree of certainty (Young, 1976; Walker, 2005). Reworked charcoal can be a major source of error (Blong and Gillespe, 1978). Nevertheless, because the technique has been so widely used its limitations are well understood and it can provide a useful correlation with other techniques (Page et al., 2007).

4.11.2 Carbon 14 Result

Some charcoal fragments between 5 – 10 mm in length were collected from the charcoal lens in Terrace 2 at the Brogers Creek exposure (Figure 4.17). These were sent to Beta Analytic Laboratory Miami for analysis with laboratory number of Beta-283860. The charcoal provided a calibrated age of 5590 to 5450 BP (95% Probability).

4.12 Optically Stimulated Luminescence (OSL) Dating

4.12.1 Background

Over the past three decades, luminescence techniques have been developed which directly date the time of deposition of the sediment. There are two types- Thermoluminescence (TL) and Optically Stimulated Luminescence (OSL) (Walker 2005).

In essence, luminescence dating is based on an understanding that natural radiation is absorbed by sediment after deposition. The energy from this radiation is absorbed by the deposited material and displaces electrons into a higher energy state where they are trapped-the older the sample the more electrons that are trapped. These electrons can be released to a lower energy state by heat or light in the laboratory. However, for reliable dating, the sediment must have been exposed and well 'bleached' by sunlight prior to burial to zero the luminescence signal (e.g. Prescott and Robertson, 1998; Walker, 2005).

Until the advent of OSL, it has been extremely difficult to reliably date young, water lain fluvial sediment (Walker, 2005). TL, which was the earliest form, was often unreliable for dating young fluvial sediment, due the long time interval required for thorough bleaching (Galbraith et al., 1999; Prescott and Robertson, 2008). However, the increased sensitivity of OSL has meant a reduction in the required bleaching time (Chandra et al., 2007) and statistical models have been developed, which can accommodate for bleaching variability (Roberts and Galbraith, 2006). Never the less, errors from partial bleaching are still a recurrent problem (e.g. Bailey and Arnold, 2004; Rodnight et al., 2006).

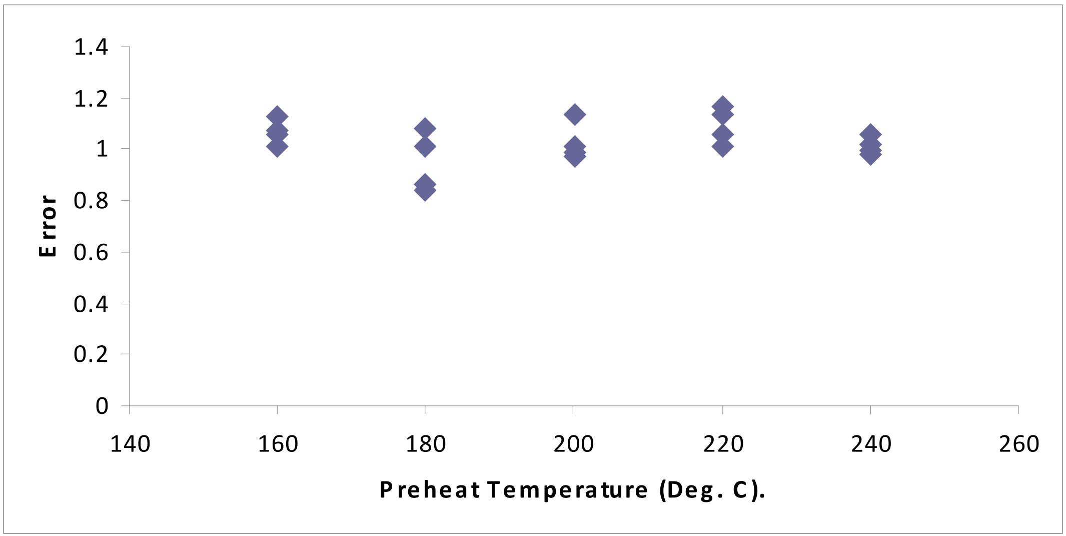
The principal advantage of OSL dating is that it can provide a reliable age from the present to about 100, 000 years (Tsukamoto et al., 2009). Another advantage is that it works directly with the river sediment, so there is no shortage of dating material, with quartz being the sediment of choice. Even if quartz is not available, then other minerals such as feldspars can be used (Prescott and Robertson, 2008).

4.12.2 Method

One OSL sample was collected from each of the three terraces at the Brogers Creek exposure and one from each of the two terraces at Bendeela. All the samples were collected from the base of each sedimentary sequence. The OSL samples were collected in steel tubes of 200 mm in length and 90 mm in diameter, and these were either hammered into a vertical terrace exposure or collected from auger holes carefully prepared to reduce the risk of contamination. Dating was undertaken at the University of Wollongong's OSL laboratory. Approximately 40 mm of sediment was removed from each end of the sample tubes, as these areas were most at risk of exposure to light during collection. The two ends of the sample was utilised to determine water content and environmental dose rate.

The middle section, which had not been exposed to light, provided the sand fraction for OSL dating. Carbonates and organic constituents were removed using hydrochloric acid and hydrogen peroxide respectively, as this material was not representative of the depositional environment and also attenuates radioactivity (Walker, 2005). Wet sieving of the samples was undertaken due to the high clay content and also to obtain the 180 - 212 µm quartz fraction. Density separation was undertaken using sodium polytungstate solution to remove heavy minerals and feldspar. The quartz fraction was dried and etched with hydrofluoric acid to remove the alpha rind. The sample was then dried and sieved to remove any grains under the 180 µm size.

All OSL measurements were undertaken using an automated RISO TL/OSL reader at the University of Wollongong. A small portion of grains was bleached in the sun for a total of 48 hours. 100-150 gains were mounted on 24 disks using a 0.5 mm mask and applied using silicon oil. These grains also provided analysis for the presence of feldspar as well as the optimum preheat temperatures (Graph 4.6), dose recovery and recycling ratios.



Graph 4.6: Preheat Temperatures and Associated Error.

The results of these tests indicated that the best pre-heat temperature should be 240 °C and that the cut heat should be 160 °C. However, as these samples were thought to be young, it was considered safer to use a lower preheat of 180 °C to reduce the possibility of thermal transfer of electrons (Zhang et al., 2003; Walker, 2005).

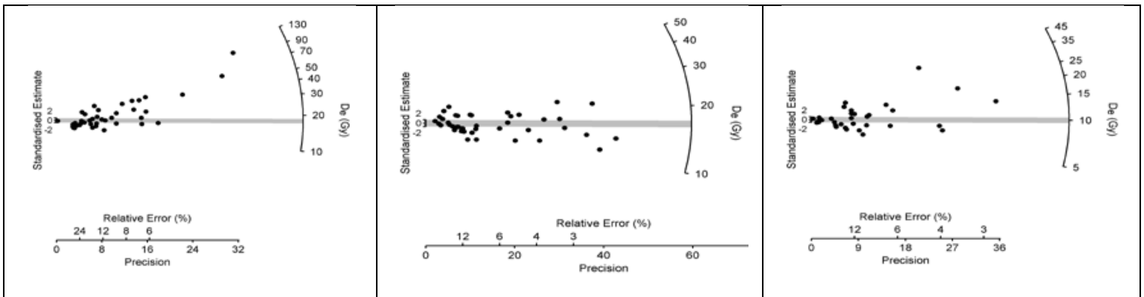
Analyses were conducted using the single aliquot regenerative dose (SAR) protocol developed by Murray and Roberts (1998) and Murray and Wintle (2000). A total of 48 stainless steel disks, containing between 3 and 8 grains, were prepared for each of the sites using a 0.3 mm mask. It was determined that a pre-heat of 180 °C for 10 s was required before the natural and regenerative dose and a cut heat of 160 °C for 5 s prior to each sensitivity measurement being taken. Irradiation of the samples utilised calibrated ^{90}Sr/^{90}Y beta sources.

For dosimetry measurements, sample was crushed to a fine powder. Alpha counting was perform using approximately 2 mm of sample was placed on top of a zinc scintillant and then counted using TSAC Readers. The samples were run until a minimum of 2000 counts was reached. Beta counting was performed on a Risoe GM 25-5 Beta Counter and the samples were run using 24, 1 hour cycles. Beta attenuation factors were taken from Mejdahl (1979) with dose correction factors being determined using Adamiec and Aitken (1998). The cosmic dose rate was calculated from Prescott and Hutton (1994).

As the samples were thought to consist of some grains which were thoroughly bleached and others which were only partially bleached at burial (Roberts and Galbraith, 2006). Therefore, all aliquots were run using the minimum age model. Certain aliquots were rejected if their De was close to zero as this would underestimate the age of the sample. In the case of Terrace 1, five grains were rejected and in Terrace 3, three grains were rejected.

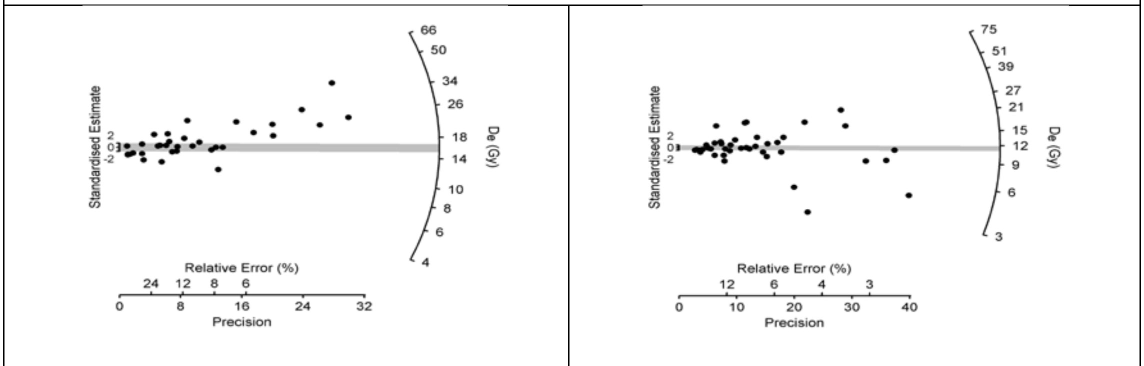
4.12.3 OSL Results

Radial plots for all samples are shown below (Figures 4.21 and 4.22). The values with the highest precision and smallest relative errors are located closest to radial axis. The shaded region shows De values that are within the 2σ confidence interval.



UoW 472-BR1 | UoW 473-BR2 | UoW 474-BR3

Figure 4.21: Radial plots of the results for Brogers Creek.



UoW 484-BH1-5 | UoW 483-BH2-5

Figure 4.22: Radial plots of results from Bendeela.

4.13 Results Summary

Dating Summary

The table below indicates the ages of the terraces and the parameters which were applied in the analysis.

UoW Log #	Alluvial Site Name	Depth (m)	K (%)	U (ppm)	Th (ppm)	Cosmic (Gy/ka)	Dose Rate (Gy/ka)	Age (ka)	Overdispersion (%)
UoW472 – BR1	Brogers Creek Terrace 1	5.0 +/- 0.1	1.54 +/- 0.10	3.47 +/- 0.13	6.63 +/- 0.44	0.154 +/- 0.130	6.93 +/- 0.97	2.855 +/- 0.438	101 +/- 12
UoW473 – BR2	Brogers Creek Terrace 2	4.7 +/- 0.1	1.24 +/- 0.07	3.64 +/- 0.14	6.37 +/- 0.43	0.156 +/- 0.130	7.77 +/- 0.19	3.529 +/- 0.229	57 +/- 7
UoW474 – BR3	Brogers Creek Terrace 3	2.0 +/- 0.1	1.47 +/- 0.10	2.65 +/- 0.16	10.51 +/- 0.57	0.184 +/- 0.142	3.64 +/- 0.40	1.602 +/- 0.210	88 +/ 12
UoW484 – BH1-5	Bendeela Hole 1	5.1 +/- 0.1	1.48 +/- 0.09	2.56 +/- 0.11	8.48 +/- 0.39	0.153 +/- 0.124	4.81 +/- 1.18	2.113 +/- 0.537	84 +/ 11
UoW483 – BH2-5	Bendeela Hole 2	5.6 +/- 0.1	1.41 +/- 0.08	2.52 +/- 0.11	6.02 +/- 0.39	0.148 +/- 0.144	3.81 +/- 0.55	1.984 +/- 0.321	92 +/ 10

Table 4.5: OSL Results Summary

Radiocarbon Date for Terrace 2 Brogers Creek.

Beta Analytic Laboratory Log Number	Alluvial Site Name	Depth (m)	Age (ka)
Beta-283860	Brogers Creek Terrace 2	4.2 +/- 0.1	5590 to 5450 BP (95% Probability).

Table 4.6: ^{14}C Result.

Channel and Floodplain Summary

Samples	Locations					
	Carrington Falls	**Upper River**	**Willabrook**	**Brogers Creek**	**Cockrane's Farm**	**Bendeela**
Gradient from DEM	0.0040	0.0100	0.0080	0.0040	0.0015	0.0015
Floodplain Width (m)	Not Applicable	Not Applicable	300	450	1000	480
Channel Width (m)	30	40	62	87	110	89
Channel Depth (m)	2.8	2.2	6.6	5.6	9.4	3.4
Cross Sectional Area (m^2)	88	88	396	487.2	1034.0	302.6
Average Boulder/Cobble Size	Clean Channel	367.4 mm	346.46 mm	202.56 mm	200.16 mm	Not Accessible
Average Depth of Sediment	Clean Channel	Not obtainable	1.3 m	4.4 m	7.1 m	6.0 m
Average mean grainsize (μm)	Not Applicable	Not Applicable	226.5	57.3	49.3	99.54

Table 4.7: Channel and Floodplain Results Summary.

CHAPTER 5

Discussion

5.1 Introduction

This section interprets what the results have revealed about the history of the Kangaroo River—how, when and why it has changed throughout the late Quaternary. An integral part of this analysis has been to evaluate the long term interplay of the different variables which have shaped the river's form over time. The reliability of the field and laboratory techniques has also been considered.

5.2 Downstream Trends

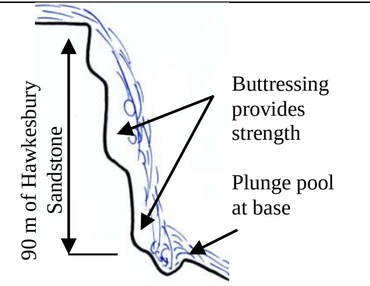
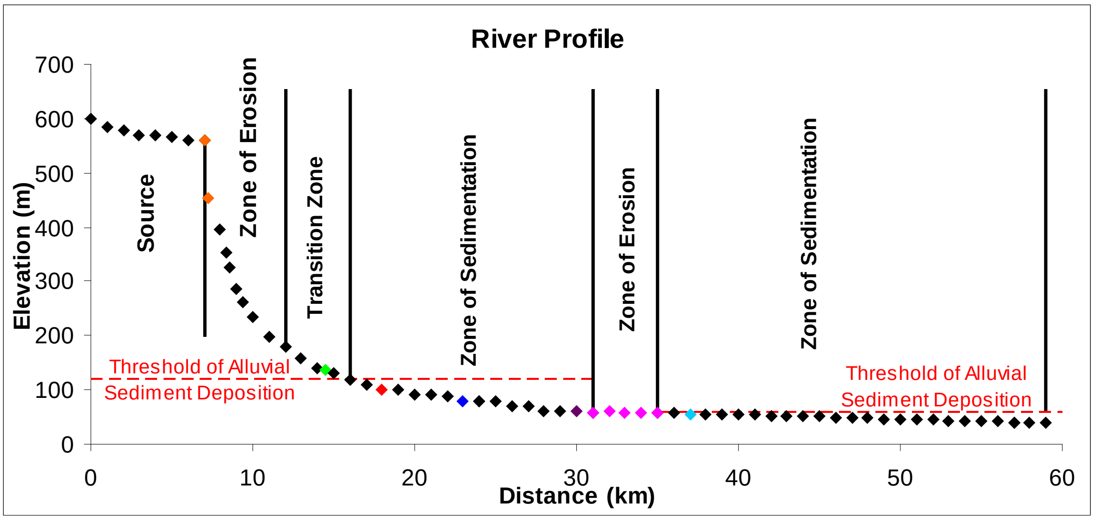


Figure 5.1: Buttressed Waterfall

As with many rivers on the Illawarra, the only significant change in gradient happens within a very short segment of the river (Young and Nanson, 1982). At Carrington Falls the river drops 90 metres over a near vertical cliff face (Figure 5.1) and then descends a further 180 metres through steep rapids. This occurs within 3.2 % of the river's total length yet represents 48 % of the river's total drop in elevation (Young, 1985). The gradients above and below this section are almost identical being composed of many gently graded pool and riffle sequences (Figure 5.2).

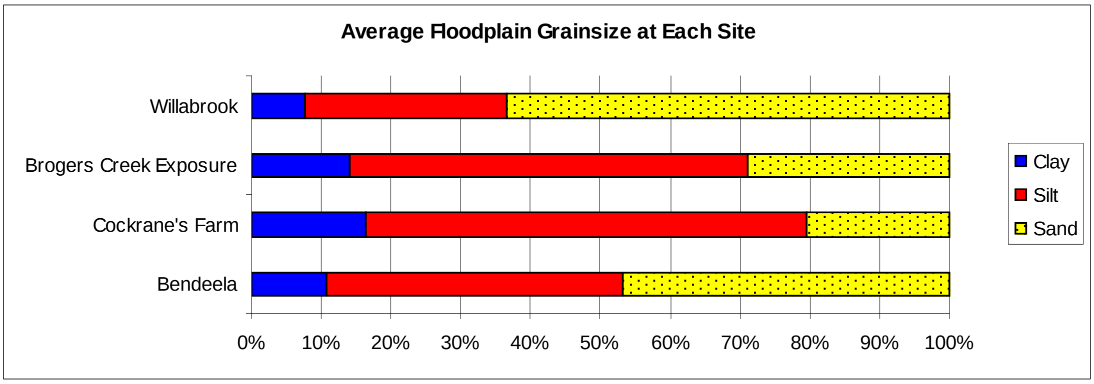


Legend: * Carrington Falls * Upper River * Willabrook * Brogers Creek

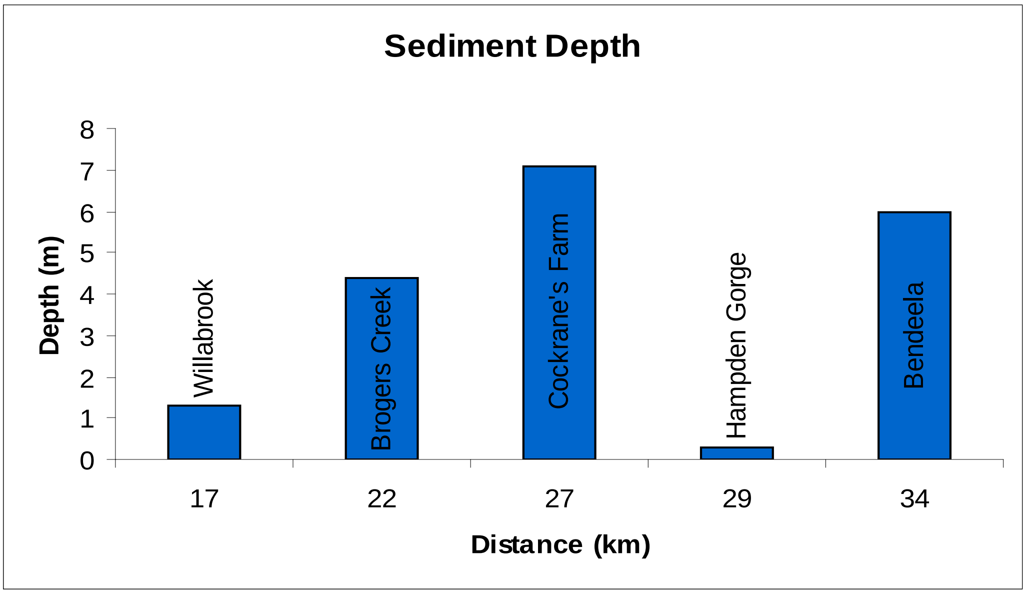
* Cockrane's Farm * Hampton Gorge * Bendeela

Figure 5.2: River Profile: Derived from DEM.

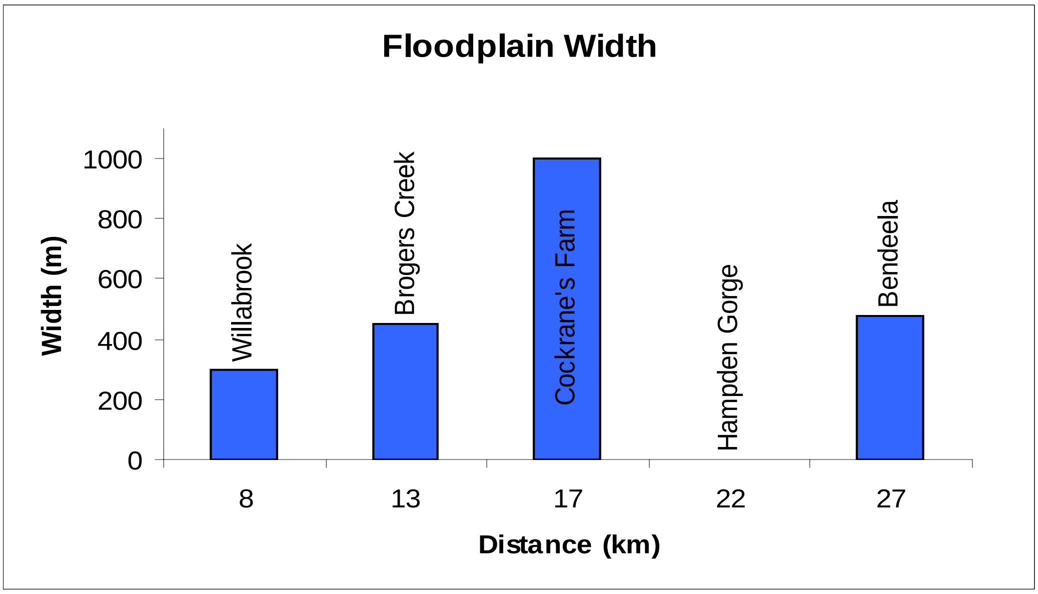
The energy from Carrington Falls directs the deposition of sediment downstream on the Kangaroo River as far as Hampden Gorge with the sediment becoming progressively finer grained (Graph 5.1), thicker (Graph 5.2) and wider (Graph 5.3). The narrow gorge at Hampden funnels and re-energises the river over the next four kilometres, so that when it emerges from the gorge at Bendeela, the trends begin again.



Graph 5.1: Downstream Fining of Floodplain Sediment.

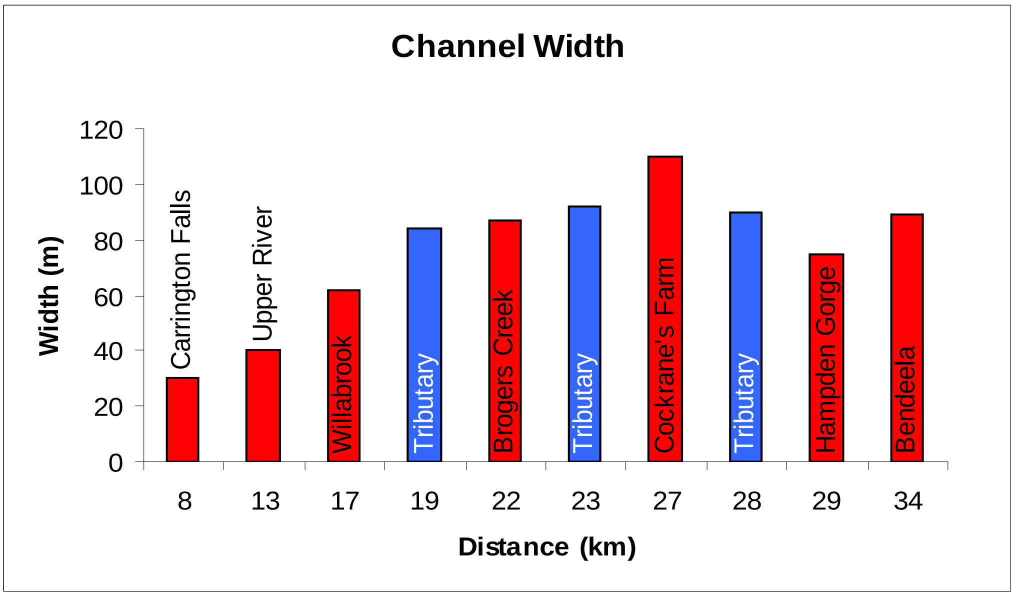


Graph 5.2: Downstream Tends in Sediment Depth



Graph 5.3: Downstream Floodplain Widths.

The only statistic which does not change gradually downstream is the channel width. Channel width changes in a step wise fashion as each new tributary enters the Kangaroo River, increasing its capacity as far as Cockrane's Farm. Below this point, both channel width (Graph 5.4) and capacity (Table 4.7) decrease, due to the confinement of Hampden Gorge.



Graph 5.4: Downstream Channel Widths.

5.3 The Individual Response of the Alluvial Sites

The analysis of sediment from the alluvial sites has provided markers as to how discrete reaches of the river have functioned over time. Each site shows that it has responded in a distinctly different way to changing conditions.

The average percentage of sand across each site varied downstream. Willabrook was composed of 63 % sand. Further downstream, the Brogers Creek exposure contained 24 % sand whereas, on the wide valley floor, Cockrane's Farm had only 21 % sand. With the resurgence in fluvial energy after Kangaroo River's lateral constriction in Hampden Gorge, Bendeela had a sand content of 45 % (Figure 5.3).

Figure 5.3: Hampden Gorge: Lateral Constriction.

As the depth of sediment preservation increased downstream, there was also a longer record of past events. At Willabrook, where the storage was restricted, most holes showed a single fining up sequence from one event, whilst the terraces at the Brogers Creek exposure contained a record of at least two events. At both Cockrane's Farm and Bendeela, there were many fluctuations in grainsize, as multiple events were preserved. From this information, a pattern emerged, as to how each section of the river has regulated its form over time.

In the middle of the flood plain at Willabrook, the sediment coarsened upwards. This suggests that the middle section has acted as a drainage divide and that either side could have been used as the main channel under certain flow conditions (Figure 5.4).

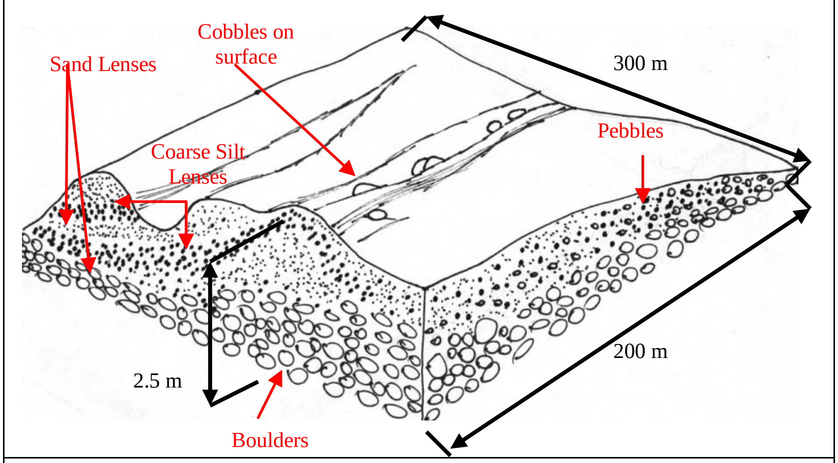


Figure 5.4: Schematic block diagram of flood plain at Willabrook indicating energy changes along and across-bed to suspended load.

Analysis of the stratigraphy and topography of the Brogers Creek exposure shows that there have been three, distinct channel migration phases of the Kangaroo

River. Terrace 1 is highly, mottled silt, Terrace 2 is fine, orange sand whilst Terrace 3 is relatively unweathered silt. Topographically, Terrace 1 is slightly higher in elevation than Terrace 2 and both are significantly higher in elevation than Terrace 3 (Figure 4.17). The difference in topography and grainsize suggests that the migration of the channel may have been the result of energy fluctuations, with the coarser sediment in Terrace 2, indicating that it was formed by the most energetic event. The unweathered and lower elevation of Terrace 3 indicates that by the time of its formation the river was relatively smaller. The LiDAR image below indicates the alignment of the prior course of the Kangaroo River (Figure 5.5). It should be noted that after about 1.6 ka, there has been a major avulsion of the river channel to its present position.

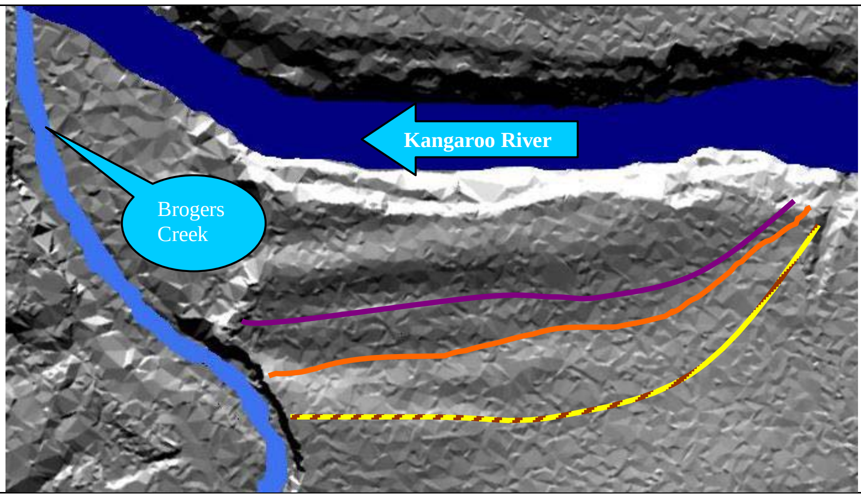


Figure 5.5: Following the topography of the terraces, lines indicate the most likely position of the three past palaeoflows.

Legend:
BR1 2.86 +/- 0.44 ka
BR2 3.53 +/- 0.23 ka
BR3 1.60 +/- 0.21 ka
(OSL Ages)

The history of the river at Cockrane's Farm was more complex. The sand lens located at the bottom of each auger hole indicates that earlier events were more energetic, so that water and sediment flooded the entire area. However, later events seem to have been less intense and inundations have been restricted to low points on the floodplain. More recently, activity has been increasingly confined to the area adjacent to the present channel and vertical accretion has been the dominant mode of floodplain development (Graph 4.3; Figure 4.18).

The hole, adjacent to the river at Cockrane's Farm, had a depth of 8.6 m and had six fluctuations. The hole nearest the river at Bendeela went to an average depth of 6.3 m and also showed six fluctuations. This indicated a similar amount of activity at both ends of the Hampden Gorge. The only significant difference was that the sediment above the gorge at Cockrane's Farm was mostly fine silt-in keeping with a backwater effect while there was a higher proportion of sand at Bendeela with the higher energy.

5.4 Sediment Colour

Sediment colour is an indicator of the relative age of the material, fluctuations in the water table and mineralogy (McKenzie et al., 2004). Moving downstream, distinct colour changes were observed suggesting different depositional conditions and time of burial.

The best location to see soil development was at the terraces of Brogers Creek, which showed three distinct colour changes (Figure 5.6). Terrace 3 was purple/brown and rich in organic material, suggesting an early stage of development. Terrace 2 was orange suggesting the oxidation of iron and finally Terrace 1 was highly mottled with roughly equal amounts of grey, orange and brown. The grey sections were where the iron had leached whereas the orange patches were sites of iron concentration. Mottling and oxidation indicated a fluctuating water table during wetter and drier periods (Jacobs et al., 2000).

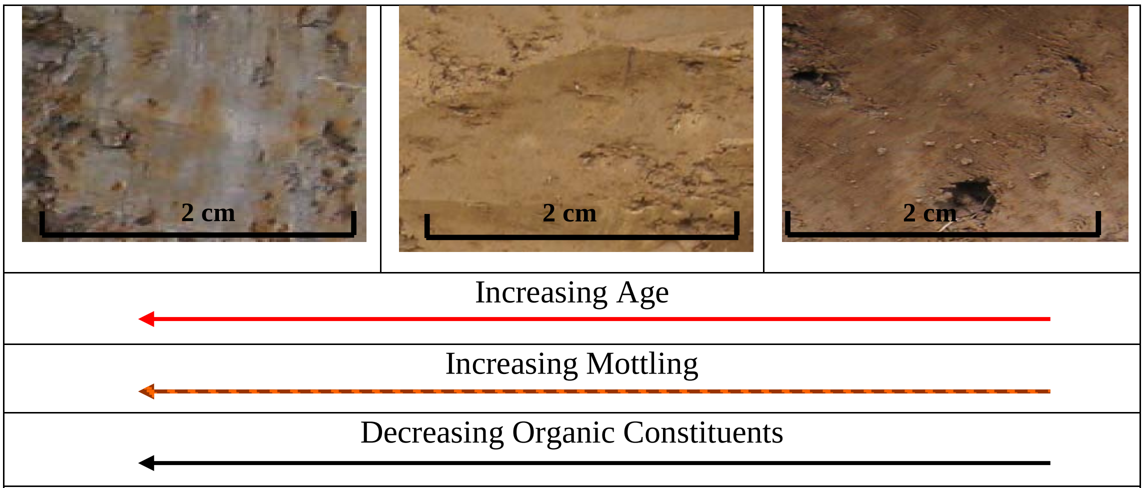


Figure 5.6: Brogers Creek Terraces One to Three from left to right.

Sediment from the other sites was compared to these categories. At Cockrane’s Farm, the sediment was largely mottled, which gave it a similar appearance to the sediment from Terrace 1 at Brogers Creek. This suggested that their ages were similar and they had been exposed to similar conditions since burial.

Figure 5.7: Soil Formation: homogenous at Willabrook, mottling at Cockrane's Farm, homogenous at Bendeela as shown from left to right.

Both Willabrook and Bendeela (Figure 5.7) were composed of a largely homogenous, orange/brown sediment, suggesting that fluctuations in the water table have been minimal at these sites. Their colour was mid way between Terraces 2 and 3 at the Brogers Creek exposure but with a coarser grain size.

Walker and Coventry (1976) developed a sequence of soil profile development as a means of dating river sediment, which has been used widely to date rivers along the east coast of NSW. All the above soil variations from these terraces have the characteristics of Walker's organic rich cumulic stage and as such his theory would date the soils as mid to late Holocene (Figure 5.8).

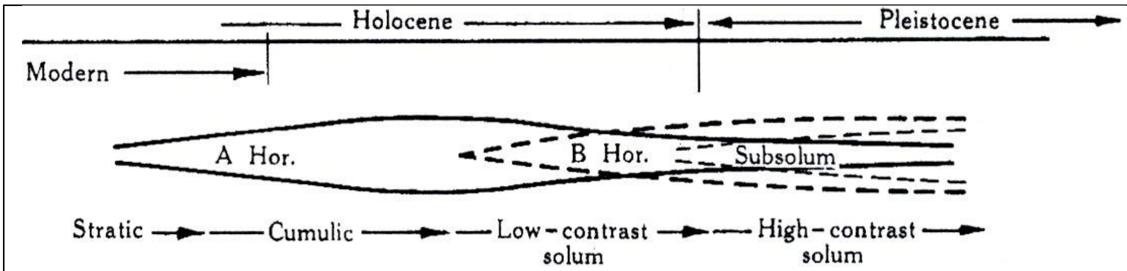
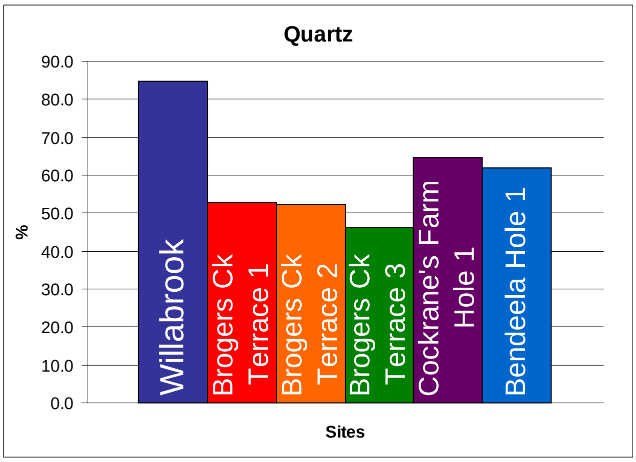


Figure 5.8: Timescale of soil development from Walker and Coventry, 1976.

5.5 Mineralogy

There was a variety of minerals in the river sediment, which was representative of the surrounding geology as well as the units over which the river was flowing. Refer to Graph 4.6 for the mineral composition at each site.

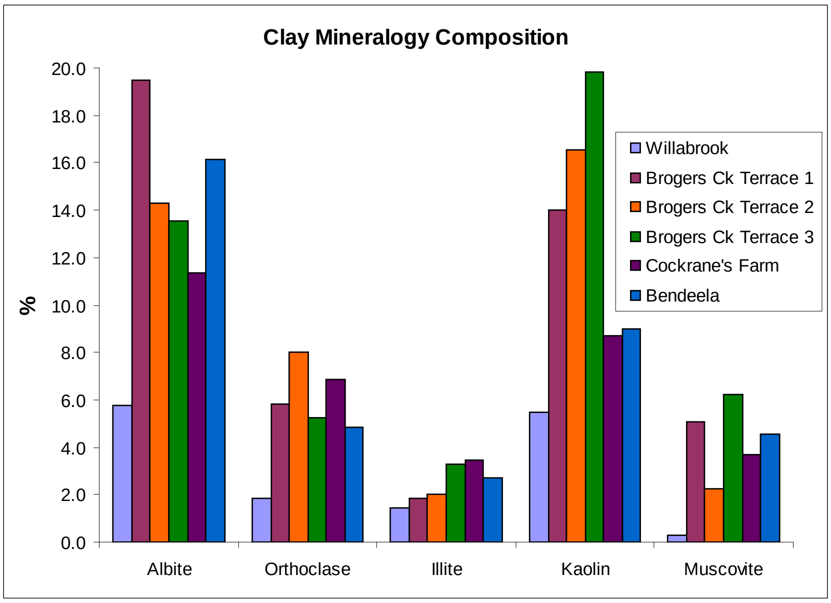
Due to its hardness and erosion resistance combined with its prevalence in the rock units, quartz was by far the most abundant mineral. Moving downstream, the concentrations initially dropped from around 85 % at Willabrook to approximately 50 % at the Brogers Creek exposure, before rising again to around 65 % at Cockrane's Farm and then decreasing slightly to 61 % at Bendeela (Graph 5.5).



Graph 5.5: Quartz mineralogy moving downstream through the alluvial sites.

The change in quartz concentrations can be explained by the varying mineralogy of the different geological units. At Willabrook, the river has just cut down into the upper Berry Siltstone, after flowing through the quartz rich Budgong Sandstone and Hawkesbury Sandstone. By the time Brogers Creek is reached, the river has flowed for 6 km, through the lower portion of the Berry Siltstone and the percentage of quartz has dropped, due to dilution with clay minerals. At Cockrane's Farm, there is a spike of quartz again, due to the river flowing into the quartz rich Nowra Sandstone. Bendeela shows a slight decrease in quartz content again, as the Kangaroo River cuts into the quartz deficient Wandawandrian Siltstone at this point.

The clay composition was much more variable (Graph 5.6). Over time clays break down into simpler constituents (Summerfield, 1991). In the past, clay has been utilised to obtain the relative age of terraces and the degree of soil formation across different locations (Walker and Green, 1976). The relatively high percentage of kaolin at Brogers Creek (14 – 20 %)



Graph 5.6: Clay Mineralogy.

suggests the terraces are weathered and relatively old or have stored reworked weathering products. However, in this situation there are a number of other factors which need to be considered. The process of converting illite to kaolinite takes tens of thousands of years. As the OSL dates show that the terraces at the Brogers Creek exposure and Bendeela are late Holocene, this conversion from illite to kaolinite could not have taken place in situ. Therefore, this change must have already taken place upstream in some of the rocks, from which the sediment was derived. The upper most units of the Hawkesbury and Narrabeen sequences have 30 – 70 % kaolinite (Bowman, 1974) with the majority being formed during the Late Tertiary to Mesozoic (Chivas and Bird, 1995) and these units are the most probable source. These results illustrate the problems associated with dating terraces, on the basis of clay mineralisation, without other dating evidence.

In summary, the high percentage of kaolin suggests that the terraces are much older than they actually are. The clay minerals appear to have been reworked along the length of the river and so they cannot be used as proxy dating for the alluvium.

5.6 From Trees to Charcoal Fragments

During sampling, most sites yielded varying amounts of charcoal with the highest concentrations, being related to the layers containing the highest percentage of coarser sediment. This suggests that a steady stream of charcoal material has flowed downstream, under stable conditions, with regular discharge.

Terrace 2 at the Brogers Creek exposure, contained a significant charcoal lens (Figure 5.9). This charcoal may have come from an extensive bushfire, followed by a rain event which washed the charcoal downstream. This is a climate pattern that occurs periodically in Australia (Young, 1986). On the Woronora Plateau, Young (1986) found that even small, magnitude floods following bushfire, stripped the mire surface of vegetation and there is a well documented history of both small and large magnitude flood events in Kangaroo Valley (Bayley, 1953; Hilder, 1988).

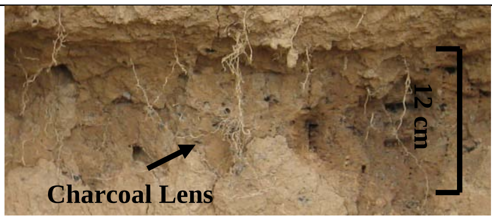


Figure 5.9: Charcoal Lens at Brogers Creek Exposure.

5.7 How the Tributaries Affect Floodplain Development

The step wise changes in channel capacity (Graph 5.4) prompted an investigation of the confluence of the three tributaries with the Kangaroo River, using a combination of LiDAR and fieldwork. Moving downstream the three tributaries are Gerringong, Brogers and Barrengarry Creeks (Figure 4.20). Where the position of the confluence changes under high magnitude flow regimes, the area of movement has been marked in red and has been defined as a zone of disequilibrium.

5.7.1 Gerringong Creek

At the confluence of Gerringong Creek and Kangaroo River, lateral migration and alteration has occurred, as a result of different flow conditions. Under normal flow conditions, Gerringong Creek joins the Kangaroo River at approximately right angles. However, during higher flows, Gerringong Creek is deflected away from its normal point of entry and joins Kangaroo River further downstream. This is indicated by the boulder splay deposit, which represents a zone of disequilibrium (Figure 5.10). This deflection happens, because Gerringong Creek has a gradient of 0.0153 m/m whilst that of the Kangaroo River is 0.0080 m/m, making the gradient of Gerringong Creek approximately twice that of the Kangaroo River at this point.

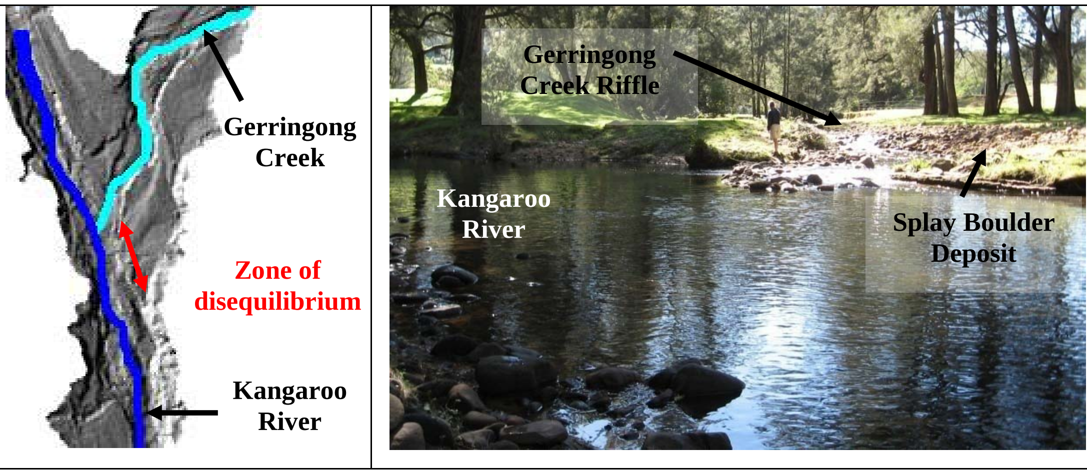


Figure 5.10: Gerringong Creek Tributary.

5.7.2 Brogers Creek Exposure

The confluence of Brogers Creek with Kangaroo River has an expanse of multiple hummocks that cover ~ 187, 500 m^2 and this hummock area represents a zone of disequilibrium (Figure 5.11). The sediment here has the appearance of an alluvial fan, a deposit which normally occurs, where there is a sharp drop in gradient or at the entrance to a standing body of water (Knighton, 1998)-neither of which exists at this point. The gradient of the Kangaroo River at this location is 0.0040 m/m whilst Brogers Creek has a very similar gradient of 0.0050 m/m.

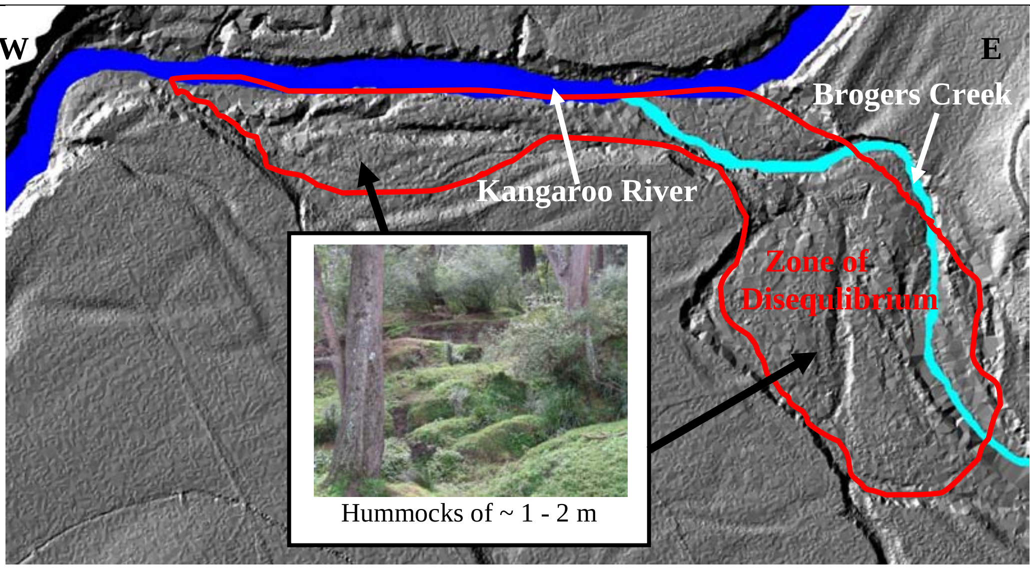


Figure 5.11: Brogers Creek Tributary.

5.7.3 Barrengarry Creek

Between Cockrane's Farm and Hampden Gorge, Barrengarry Creeks flows directly into the Kangaroo River with neither deviation nor disequilibrium. The gradients of both the Kangaroo River and Barrengarry are approximately the same, each having a gradient of 0.0015 m/m. Upstream of its confluence with the Kangaroo River, outcrops of Nowra Sandstone are clearly visible (Figure 5.12).

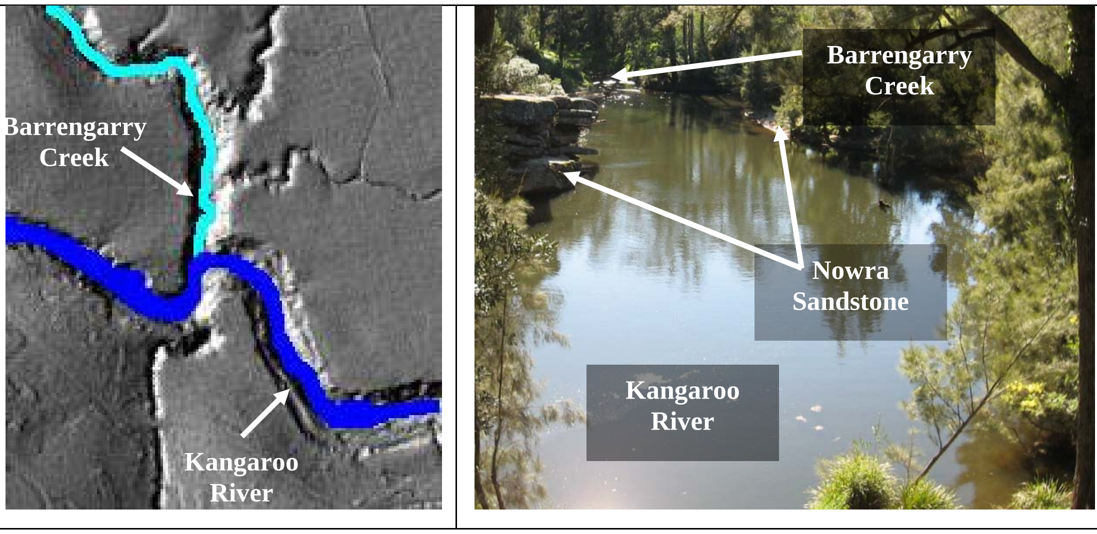


Figure 5.12: Barrengarry Creek Confluence with the Kangaroo River.

In summary, Gerringong and Brogers Creeks exhibit disequilibrium at their confluences with the Kangaroo River. Barrengarry Creek, on the other hand, makes a direct entry.

5.8 Transition Zone

Understanding the location and characteristics of the different units provides the key to deciphering the changes in floodplain development and the mode of tributary entry along the Kangaroo River. The three dimensional diagram (Figure 5.13) covers the critical section of the river. The diagram shows that the Berry Siltstone has been eroded off just below the point where Brogers Creek enters the Kangaroo River. Upstream at Willabrook, at the confluence with Gerringong Creek and at the Brogers Creek exposure, the river has been flowing through the relatively soft Berry Siltstone. Downstream from this point, before the confluence with Barrengarry Creek and through the Hampden Gorge, the Kangaroo River is cut into the Nowra Sandstone. With this information it is possible to explain the results.

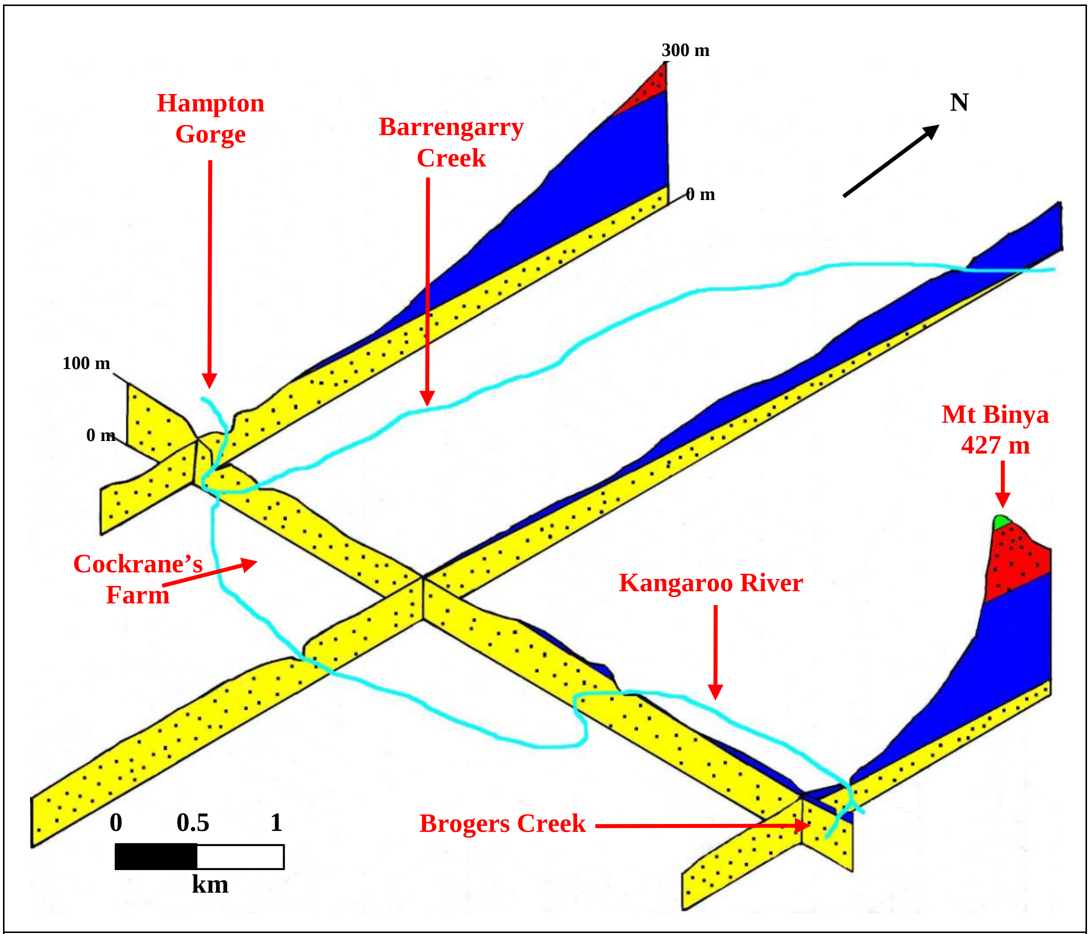
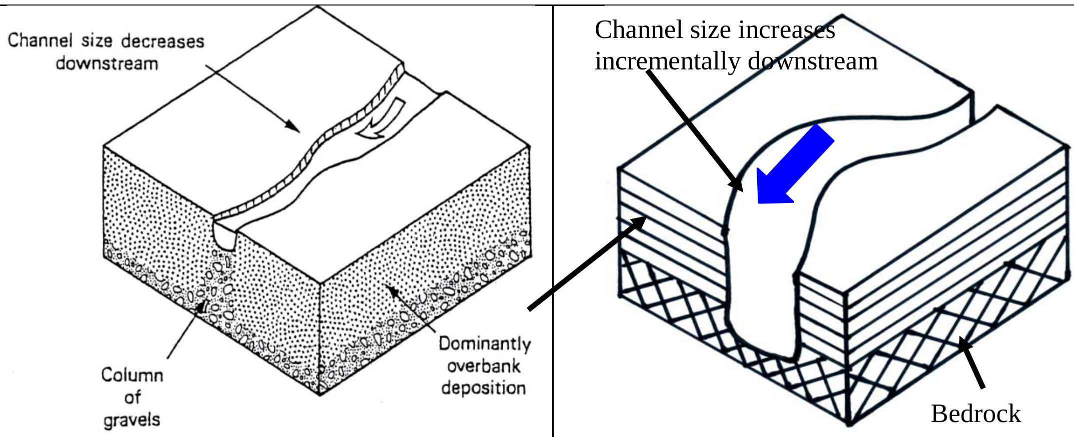


Figure 5.13: Geological Cross Section.

According to the traditional view of floodplain development, the width of the floodplain increases downstream and the river channel migrates laterally across the floodplain to dissipate excess energy (Mackin, 1937; Leopold and Wolman, 1954). However, the low floodplain to channel width (Table 4.4) means that migration is limited for the Kangaroo River. In the softer Berry Siltstone, small amounts of migration can occur. However, in the relatively hard, erosion resistant Nowra Sandstone, vertical accretion is the dominant mode due to increased structural constraint.

The latter point is illustrated by the results from Cockrane's Farm, where most of the activity is confined to within approximately one hundred metres of the channel. This floodplain phenomenon of channel stability and fine over bank deposits was reported by Young and Nanson (1982) on the coastal streams of the Illawarra. In that location, it was cohesive sediment on the channel edges which restricted river movement, whereas along the lower Kangaroo River, migration is restricted by a degree of incision into bedrock with cohesive floodplain alluvium above. This has resulted in the formation of a very stable channel (Figure 5.14).



Illawarra cohesive mud confinement (Young and Nanson, 1986).

Kangaroo River bedrock and alluvial confinement.

Figure 5.14: Dominantly overbank deposits and confinement in two different settings.

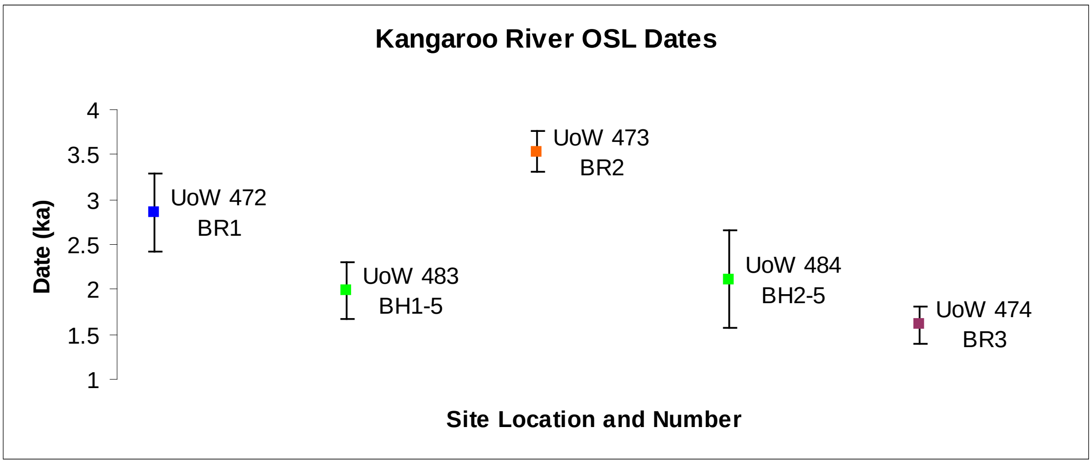
The changing mode of entry of the different tributaries also reflects the changing units. Gerringong and Brogers Creek are cut into the relatively soft Berry Siltstone and so migration and valley widening have been an option whereas Barrengarry Creek is confined by Nowra Sandstone.

The “alluvial fan”, which has formed at the confluence of Brogers Creek, illustrates the location where the two units converge. The fan like shape of the area, which is covered by the hummocks, suggests that during high flows, sediment is flushed from Brogers Creek and accumulates here. When this happens, Brogers Creek is blocked from it normal entry point into the Kangaroo River and is forced to utilise other channels (Figure 5.11).

In summary, the mode of floodplain deposition and tributary entry are controlled by the degree of structural constraint which is imposed by the different lithology through which the Kangaroo River flows. This means, that the river’s form can only change rapidly in response to changing conditions in the Berry Formation.

5.9 OSL Terrace Chronology

The OSL dates for basal terrace formation all fell within a very small (3.5ka to 1.6 ka) range, with the three dates from the Brogers Creek exposure, straddling the two dates from Bendeela (Graph 5.7). The weathering profiles at both sites indicated that they were all mid to late Holocene in age (Figure 5.8) and the OSL dates have provided further confirmation.



Graph 5.7: Kangaroo River OSL Dates and Sites.

At Bendeela, ages of 1.984 +/- 0.321 ka and 2.113 +/- 0.537 ka were obtained, suggesting that these two terraces have been formed from the same event, even though they have a difference in elevation of around 0.5 m (Figure 5.15). The field observations also showed similarities between the two holes. They were both fluvially active sites, the soil development looked very similar and they shared distinct lenses of fine, loamy sand. From Young's 1976 survey, this sediment would have been at least seven metres above the floodplain, at the time of terrace formation. Only a significant flood event would have overtopped this elevation. Such an energetic event could easily have covered both terraces, despite the difference in elevation. The OSL dates are also very close to the radiocarbon date of 1790 +/- 90 BP, which Young (1976) obtained from 10 cm above basal gravels on the lower terrace. Therefore, the OSL dates, the field data and the earlier dating all suggest coeval terrace formation.

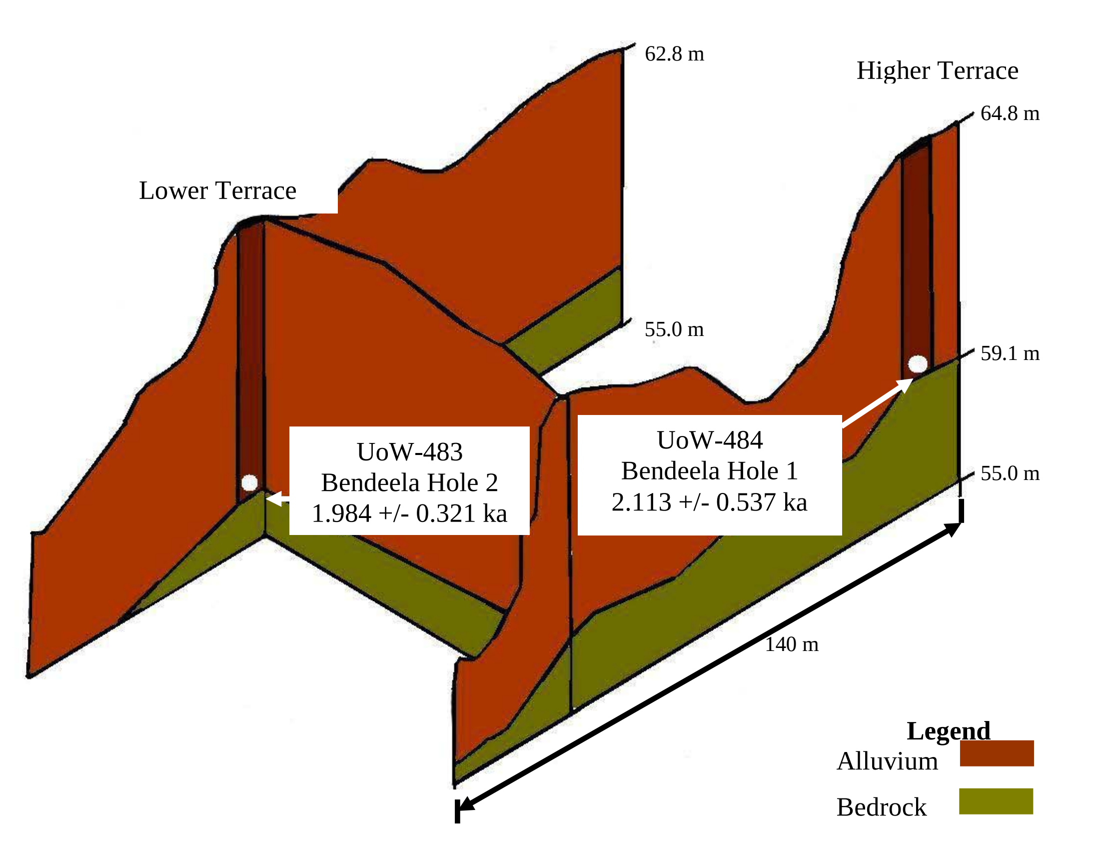


Figure 5.15: OSL depths and dates at Bendeela.

The OSL chronology from the Brogers Creek exposure exhibited some inconsistencies. The OSL dates give ages of 2.855 +/- 0.438 ka for Terrace 1, 3.529 +/- 0.229 ka for Terrace 2 and 1.602 +/- 0.210 ka for Terrace 3.

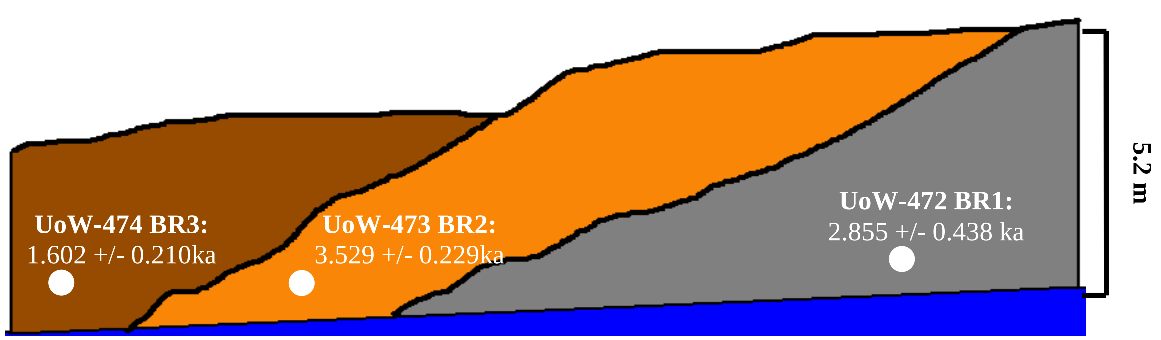


Figure 5.16: Overlapping terraces at Brogers Creek.

There is no confusion about the chronology of Terrace 3, the OSL date and the field data all indicate that this is the youngest terrace. However, the other dates-even allowing for the error-indicate that Terrace 2 is the older than Terrace 1 but the field observations contradict this order. Terrace 2 overlies Terrace 1 and therefore Terrace

1 must be older (Figure 5.16). Also the different colours of the alluvium, suggest that the terraces become older moving from Terrace 3 to Terrace 1 with the mottling becoming more prevalent (Figure 5.6).

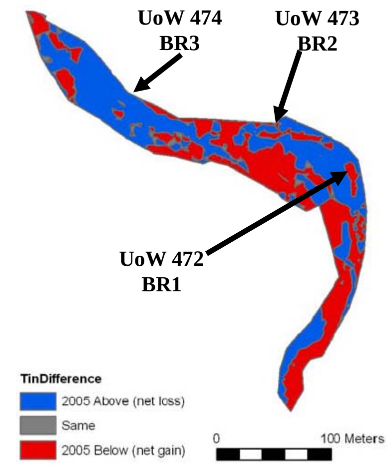
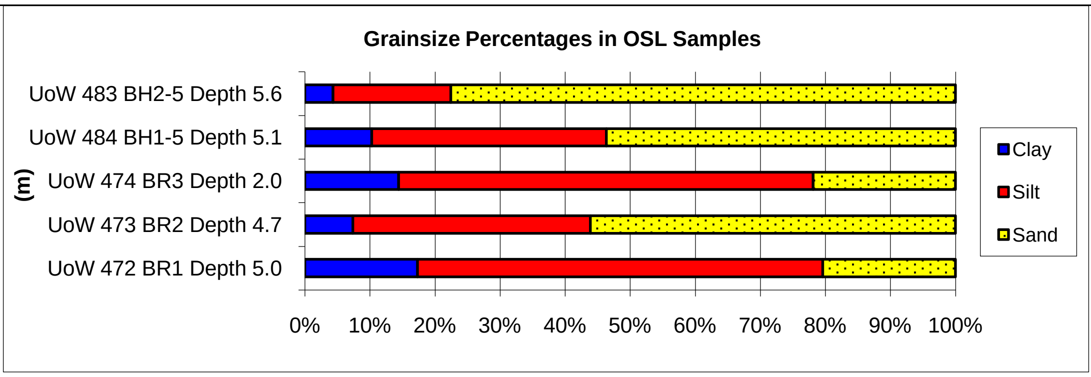


Figure 5.17: Brogers Creek exposure with approximate position of OSL Samples (Adapted from Cohen 2008).

A recent report by Cohen (2008) for the Southern Rivers Catchment Management Authority (SRCMA) reveals variable erosion has taken place along this reach of Brogers Creek between 2005 and 2008. The sample from Terrace 1 was taken from the apex of the curve and this has been identified as the point of maximum erosion (Figure 5.17), which means that some sediment may have been recently exposed to sunlight and this could have confounded the result.

Over dispersion, which was a problem in this study, has been previously explained by differences in grainsize and mode of transport. In fine grained, cohesive muds and silts, clumping may prevent internal grains from being exposed to sunlight (Lang and Nolte, 1999) while coarser fluvial sands are usually better bleached (Olley et al., 1998). Graph 5.8 shows the proportions of grainsize for each OSL sample and the results demonstrate that the relationship between over dispersion and grainsize cannot explain the problem in this study. For instance, UoW 473 BR2 contains 58 % sandy material and the over dispersion is 57% but UoW 483 BH2-5 has 21 % more sandy material yet the over dispersion is 92%. No alternative explanation for this commonly encountered problem with young fluvial sediment (Rodnight et al., 2006) fully accounted for this result.



Graph 5.8: Variations in Grainsize of each of the OSL Samples.

5.10 The Carbon 14 Date

Figure 5.18: Stratigraphic Inversion of ^{14}C and OSL Dates.

Charcoal was collected from a substantial lens of relatively large fragments approximately 0.5 m above the OSL sample and 4.2 m below the surface, in Terrace 2, at the Brogers Creek exposure. The charcoal returned a date of 5590 to 5450 BP (95% Probability), which coincided with the latter part of the Holocene Climatic Optimum, a period inferred to be a time of enhanced rainfall and stable vegetation, with limited sediment sequestration (Cohen and Nanson, 2008). The problem is that the charcoal date is ~ 2 ka older that than the OSL date however, the OSL date is in a lower stratigraphic unit (Figure 5.18).

As all five OSL dates were late Holocene, it seems probable that the carbon has been stored upstream and has later been transported and incorporated into the exposure at Brogers Creek. The fact that it forms part of a distinct charcoal lens (Figure 5.9), suggests that the charcoal has probably come from a significant event such as a bushfire and been washed downstream in a subsequent flood (Blong and Gillespie, 1978; Young, 1986). From his research, Dodson (1994) thought that these Holocene charcoal lenses were probably the result of indigenous burning as well as natural fire activity.

5.11 The Causes of Terrace Formation

The range of ages obtained from the two dated sites along the Kangaroo River are between 3.5 ka to 1.6 ka indicating that the terraces are all late Holocene. This is a much shorter history than has been found than on any of the other east coast rivers.

Catchment	Size (km^2)
Kangaroo River	330
Widden Brook	640
Bellinger River	1100
Nambucca River	1407
Clyde River	3280
Shoalhaven River	7300
Nepean River	11000

Table 5.1: Comparison of Catchment Dimensions.

This short window probably results from a combination of factors. The Kangaroo River has a very small catchment compared to the other rivers (Table 5.1). In a large catchment, it is possible to have a rain event which only affects one section, so that its effect is diluted as it flows through the system. However, the restricted input to the Kangaroo River means that local rain events can often affect the entire catchment. This is significant, because of the frequent and intense rain events which characterise the region (Table 2.2). Of particular importance is the very high discharge rate, which produces flood events in Kangaroo Valley (Cohen, 2008).

According to the OSL dates, terrace formation commenced at ~ 3.5 ka, when the Nambucca phase was waning. As there is no record of earlier sedimentation in the Kangaroo Valley and as the Holocene Gap ended ~ 4.5 ka, it is possible that these terraces represent the first sedimentation following what is thought to have been a highly pluvial period of limited sediment sequestration (Cohen and Nanson, 2007). However, as the terraces cover such a restricted time frame, it is impossible to conclude whether or not this period of sedimentation was associated with a broad climatic episode or was simply a result of local climatic events. A similar conclusion was reached by Cheetham et at (2010) and Cohen and Nanson (2008) dating the partially confined river valleys of the Widden Brook and Bellinger River respectively.

CONCLUSIONS

The study has provided information about the way, in which the Kangaroo River has changed its flow characteristics downstream and how its alluvium has responded to these changes. As the valley widened and the gradient lessened, energy reduced with sediment deposition becoming finer and thicker. This was in contrast to Hampden Gorge, which was characterised by higher energy and therefore erosion, with coarser sediment being deposited further downstream at Bendeela.

Individual sites displayed very different responses to changing conditions. In the softer units of the Berry Formation, the Kangaroo River has been able to migrate producing some lateral accretion whilst in the harder units of the Hawkesbury and Nowra Sandstones the river has been locked into a bedrock channel and, in the Nowra Sandstone, fine overbank vertical accretion has predominated.

The study also showed how the bedrock geology of the Kangaroo River controls sediment input and hence the mineral composition present in the terrace alluvium. However, it cautioned against using clay mineralogy as a proxy dating technique for terrace formation.

The OSL dates showed that terrace formation commenced shortly after the end of the Holocene Climatic Optimum and that the age range was very limited in duration from 3.5 ka to1.6 ka, with ages both above and below the restriction at Hampden Gorge being comparable. The radiocarbon date was mid Holocene ~ 5.9 ka and was thought to have been incorporated into the terraces following reworking and downstream fluvial transport.

It was thought that the limited terrace chronology stemmed from the combined effect of a very small catchment size, a low channel to floodplain width, high discharge rate and high intensity rain events. The small range of the dates for the terraces has made it difficult to conclude whether these deposits reflect the latter part of the Nambucca Phase-a pluvial period which was experienced by many east coast rivers-or were simply the product of local climatic events.

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Wollongong: 1:250000 Geological Series Sheet S156-9 (2nd Ed.): NSW Dept of Mines.

Note: all sketches and photos are by the author unless otherwise stated.

APPENDICES

Appendix A
The Locations

Name	Sample ID	Collection Dates	GPS Co-ordinates (MGA GDA 94)			
			Easting	Northing	Accuracy	Elevation
Carrington	C					
Upper Kangaroo	U	25/03/2010	34.65267	150.60420	8.7	148.2
Willabrook 1	WH1	21/04/2010	34.67876	150.59837	17.0	112.7
Willabrook 2	WH2	21/04/2010	34.67902	150.59846	12.7	102.9
Willabrook 3	WH3	21/04/2010	34.67931	150.59779	9.3	90.3
Willabrook 4	WH4	21/04/2010	34.67918	150.59819	7.2	98.1
Willabrook 5	WH5	21/04/2010	34.67888	150.59877	17.6	94.8
Brogers Creek 1	BR1	19/03/2010	34.72147	150.57324	14.6	85.9
Brogers Creek 2	BR2	19/03/2010	34.72127	150.57301	14.9	86.2
Brogers Creek 3	BR3	19/03/2010	34.72113	150.57260	34.5	81.4
Cockrane's Farm 1	CH1	07/04/2010	34.72816	150.53036	8.2	69.8
Cockrane's Farm 2	CH2	08/04/2010	34.72509	150.53200	10.8	71.8
Cockrane's Farm 3	CH3	08/04/2010	34.72702	150.53171	6.7	72.4
Cockrane's Farm 4	CH4	09/04/2010	34.73095	150.53081	8.6	70.0
Cockrane's Farm 5	CH5	09/04/2010	34.72916	150.53122	6.1	75.3
Bendeela 1	BH1	05/05/2010	34.74118	150.47350	26.0	78.4
Bendeela 2	BH2	06/05/2010	34.74228	150.47896	8.9	73.3

Appendix B
Willabrook Grainsize

Willabrook Hole 1						
Depth	% Clay	% Silt	% Sand	% Gravel	Average Size (μm)	sorting
Depth 0.4	5.95	24.47	69.57	0.00	228.78	2.38
Depth 0.9	8.53	40.18	51.29	0.00	167.07	2.26
Depth 1.1	8.87	35.22	55.90	0.00	205.98	2.25
Depth 1.3	6.90	19.40	71.40	2.40	210.55	4.89

Willabrook Hole 2						
Depth (m)	% Clay	% Silt	% Sand	% Gravel	Average Size (μm)	Sorting
Depth 0.4	10.63	34.45	54.92	0.00	213.25	1.14
Depth 0.6	12.20	38.88	48.92	0.00	154.57	1.11
Depth 1.0	8.11	25.41	65.40	1.40	226.12	3.99
Depth 1.3	6.96	24.88	66.15	2.10	249.58	4.18
Depth 1.5	9.28	30.95	58.94	0.90	179.22	3.89
Depth 2.0	8.53	27.99	63.48	0.00	239.98	2.58
Depth 2.5	5.00	21.54	71.25	2.20	320.72	4.56

Willabrook Hole 3						
Depth	% Clay	% Silt	% Sand	% Gravel	Average Size (μm)	Sorting
Depth 0.6	5.20	17.20	76.22	1.60	258.81	3.98
Depth 0.8	3.78	14.85	79.20	2.30	317.28	4.58
Depth 1.0	8.45	27.81	63.74	0.00	253.72	2.24
Depth 1.2	11.90	35.85	52.25	0.00	184.22	2.17

Willabrook Hole 4						
Depth	% Clay	% Silt	% Sand	% Gravel	Average Size (μm)	sorting
Depth 0.5	7.00	34.65	58.36	0.00	203.08	1.48
Depth 0.65	7.50	34.79	57.71	0.00	185.83	1.39
Depth 0.9	4.20	22.60	71.02	2.30	273.72	4.35

Willabrook Hole 5						
Depth	% Clay	% Silt	% Sand	% Gravel	Average Size (μm)	sorting
Depth 0.5	5.39	36.33	58.28	0.00	216.20	2.45
Depth 0.7	4.21	23.45	70.62	2.00	239.99	4.15

Brogers Creek Grainsize

Brogers Creek Hole 1					
Depth	% Clay	% Silt	% Sand	Average Size (µm)	Sorting
Depth 1.0	16.92	59.43	23.65	40.07	3.48
Depth 1.4	16.24	58.63	25.13	45.11	3.75
Depth 2.2	15.53	66.95	17.52	30.83	2.85
Depth 3.0	7.87	41.28	50.84	60.37	1.87
Depth 3.2	14.23	63.18	22.59	69.28	1.21
Depth 4.0	12.23	75.64	12.13	59.84	3.58
Depth 4.4	13.17	55.14	31.69	59.84	3.58
Depth 5.0	17.32	62.29	20.39	44.97	3.83
Depth 5.6	17.31	63.11	19.57	46.00	3.87
Brogers Creek Hole 2					
Depth	% Clay	% Silt	% Sand	Average Size (µm)	Sorting
Depth 0.8	12.21	41.21	46.59	116.61	2.59
Depth 1.2	12.93	51.63	35.44	64.75	3.13
Depth 2.2	16.04	60.73	23.22	61.68	5.54
Depth 2.6	10.93	51.84	37.24	65.50	2.49
Depth 3.7	14.89	56.88	28.23	54.72	3.87
Depth 4.0	9.43	40.74	49.83	95.22	1.36
Depth 4.2	15.06	61.28	23.66	37.75	3.06
Depth 4.7	7.37	36.53	56.10	104.87	1.05
Depth 5.0	13.75	41.66	44.59	81.87	2.32
Brogers Creek Hole 3					
Depth	% Clay	% Silt	% Sand	Average Size (µm)	Sorting
Depth 0.7	17.97	64.01	18.01	33.00	3.17
Depth 1.0	18.04	63.87	18.09	33.73	3.24
Depth 1.7	18.22	66.41	15.37	32.43	3.22
Depth 2.0	14.40	63.74	21.87	37.70	3.03
Depth 2.5	10.90	66.75	22.35	42.17	1.99

Cockrane's Farm Grainsize

Cockrane's Farm Hole 1					
Depth	% Clay	% Silt	% Sand	Average Size (µm)	Sorting
Depth 0.4	17.37	72.99	9.65	47.59	1.28
Depth 1.0	16.46	82.38	1.16	11.53	1.11
Depth 1.5	17.45	81.16	1.39	11.55	1.14
Depth 2.1	16.98	81.01	2.01	13.69	1.43
Depth 2.6	17.67	81.02	1.31	10.88	1.11
Depth 3.3	17.01	70.57	12.42	27.64	2.65
Depth 3.9	18.89	60.07	21.04	46.92	4.83
Depth 4.3	13.00	39.24	47.76	109.77	2.14
Depth 4.7	12.76	35.36	51.88	124.78	1.54
Depth 5.5	7.46	20.85	71.69	214.03	0.72
Depth 5.9	9.31	24.73	65.96	192.46	0.82
Depth 6.1	16.79	62.54	20.67	39.90	3.31
Depth 6.5	15.25	69.78	14.97	26.90	1.97
Depth 6.8	13.75	55.73	30.52	48.75	2.09

Cockrane's Farm Hole 2					
Depth	% Clay	% Silt	% Sand	Average Size (µm)	Sorting
Depth 0.8	17.83	75.67	6.49	34.55	1.56
Depth 1.0	18.38	80.55	1.07	10.99	1.22
Depth 1.3	19.89	78.25	1.86	11.61	1.29
Depth 1.7	18.80	80.01	1.19	11.25	1.23
Depth 2.1	18.50	79.86	1.64	12.01	1.24
Depth 2.9	17.61	81.22	1.17	11.30	1.16
Depth 3.6	16.31	78.23	5.47	22.12	2.17
Depth 3.8	15.48	83.41	1.11	12.36	1.10
Depth 4.5	19.65	72.32	8.03	25.39	3.06
Depth 4.9	19.17	75.98	4.86	15.66	1.75
Depth 5.2	14.08	57.94	27.98	48.60	3.24
Depth 5.7	10.44	42.33	47.24	90.30	1.61
Depth 6.5	9.12	28.23	62.64	206.82	1.14

Cockrane's Farm Hole 3					
Depth	% Clay	% Silt	% Sand	Average Size (µm)	Sorting
Depth 0.6	18.33	72.47	9.20	53.91	1.20
Depth 0.9	17.98	78.22	3.80	14.50	1.50
Depth 1.4	12.38	82.17	5.45	19.73	1.19
Depth 1.9	17.43	79.28	3.29	14.46	1.36
Depth 2.5	15.59	78.53	5.88	18.70	1.38
Depth 2.8	16.69	81.20	2.10	17.35	1.90
Depth 2.9	12.83	72.21	14.96	40.45	2.25
Depth 3.4	17.22	74.16	8.61	27.51	2.63
Depth 4.0	14.19	59.56	26.25	43.20	2.13
Depth 4.4	13.82	51.81	34.37	54.36	1.98
Depth 4.7	15.19	50.35	34.46	52.95	2.43
Depth 5.1	8.25	24.26	67.49	229.23	0.84
Depth 5.2	12.54	47.07	40.39	61.17	1.53
Depth 5.5	13.76	57.34	28.91	45.83	1.88
Depth 5.9	10.75	47.43	41.81	65.56	1.40
Depth 6.4	14.40	65.38	20.22	40.84	2.54
Depth 6.7	17.68	63.42	18.90	35.84	3.96
Depth 7.0	10.10	33.08	56.83	113.50	1.03

Cockrane's Farm Hole 4					
Depth	% Clay	% Silt	% Sand	Average Size (μm)	sorting
Depth 0.6	19.33	78.12	2.55	12.76	1.40
Depth 1.0	18.63	79.64	1.74	12.16	1.35
Depth 1.5	20.33	75.42	4.25	12.45	1.51
Depth 1.9	17.23	81.59	1.19	12.18	1.19
Depth 2.4	19.87	74.92	5.21	15.35	1.82
Depth 3.0	15.87	75.94	8.20	29.99	2.36
Depth 3.4	19.42	70.90	9.67	20.90	2.24
Depth 3.8	19.90	76.90	3.20	13.54	1.46
Depth 4.3	21.25	75.81	2.94	13.39	1.62
Depth 4.8	16.35	80.50	3.15	15.24	1.36
Depth 5.1	19.45	76.87	3.68	15.01	1.68
Depth 5.6	19.42	79.25	1.33	11.40	1.23
Depth 6.1	20.31	76.02	3.66	13.63	1.58
Depth 6.5	14.65	66.89	18.46	32.48	1.74
Depth 6.8	18.54	64.87	16.59	34.46	3.40

Cockrane's Farm Hole 5					
Depth	% Clay	% Silt	% Sand	Average Size (μm)	Sorting
Depth 0.5	18.78435	67.71909	13.49656	24.799	2.30
Depth 0.9	20.86344	69.23192	9.90464	20.802	2.28
Depth 1.4	19.19337	64.62864	16.17798	40.534	3.50
Depth 1.9	17.4231	58.6358	23.94109	41.204	3.54
Depth 2.2	16.26394	58.18454	25.55152	41.048	3.43
Depth 2.6	15.00872	56.3921	28.59918	49.571	3.57
Depth 3.1	14.71677	48.02258	37.26066	64.129	2.78
Depth 3.8	15.5248	56.54864	27.92656	45.928	3.50
Depth 4.2	15.52284	55.36237	29.1148	46.552	3.03
Depth 4.6	14.6642	45.61159	39.72422	83.048	3.80
Depth 5.1	19.18589	76.55542	4.25869	15.165	1.62
Depth 5.5	13.68508	43.12802	43.18691	112.417	3.63
Depth 6.0	9.054439	25.98205	64.96352	185.148	1.89
Depth 6.5	18.64041	65.64094	15.71865	35.161	3.14
Depth 6.7	19.01733	59.34092	21.64176	53.821	4.99
Depth 6.9	13.89153	39.98678	46.12169	135.7	4.13
Depth 7.1	15.47157	43.94575	40.58268	80.63	3.35
Depth 7.5	21.3653	53.63745	24.99725	66.678	3.20
Depth 8.0 m	16.93206	47.82975	35.23819	72.262	3.80
Depth 8.4 m	22.20471	62.71969	15.07561	39.832	3.30
Depth 8.6 m	22.56657	19.32983	58.1036	62.858	3.20

Bendeela Grainsize

Bendeela Hole 1 – Upper Terrace					
Depth	% Clay	% Silt	% Sand	Average Size (μm)	Sorting
Depth 0.3	12.95	41.55	45.50	106.70	2.62
Depth 0.9	10.89	35.41	53.69	106.00	1.15
Depth 1.4	12.08	47.40	40.52	66.64	1.80
Depth 1.8	10.63	43.15	46.22	77.16	1.43
Depth 2.0	12.01	48.99	39.01	62.98	1.90
Depth 2.2	12.16	62.07	25.76	40.94	1.83
Depth 2.3	17.77	61.24	20.98	39.75	3.62
Depth 2.5	15.51	67.42	17.07	32.28	2.69
Depth 2.8	11.87	54.18	33.95	73.04	3.45
Depth 3.2	10.55	40.32	49.13	114.79	1.82
Depth 3.8	9.57	37.76	52.67	128.94	1.48
Depth 4.2	8.95	36.89	54.16	119.80	1.19
Depth 4.6	12.07	36.93	51.01	131.31	1.69
Depth 5.0	9.31	33.24	57.45	149.71	1.12
Depth 5.2	10.27	36.06	53.67	106.57	1.17
Depth 5.5	10.04	50.76	39.20	66.74	1.56
Depth 5.6	15.58	65.10	19.32	35.50	2.87
Depth 5.7	17.11	67.27	15.62	30.73	2.80

Bendeela Hole 2 – Lower Terrace					
Depth	% Clay	% Silt	% Sand	Average Size (μm)	Sorting
Depth 0.3	7.88	25.28	66.84	170.08	2.60
Depth 0.5	10.32	48.60	41.08	66.17	1.91
Depth 1.0	12.88	44.83	42.29	72.05	1.46
Depth 1.6	11.41	38.34	50.25	83.21	1.68
Depth 2	13.08	46.03	40.89	69.88	1.45
Depth 2.1	9.79	42.43	47.77	75.35	1.15
Depth 2.3	12.35	49.80	37.84	65.79	2.19
Depth 2.5	9.36	43.62	47.01	80.07	1.29
Depth 2.9	11.17	46.98	41.85	71.49	2.06
Depth 3.4	9.11	39.28	51.61	97.51	2.20
Depth 3.9	12.02	50.69	37.30	62.23	1.60
Depth 4.4	9.10	38.88	52.02	85.76	2.21
Depth 4.7	11.72	39.83	48.45	94.74	1.65
Depth 5.2	9.88	31.86	58.26	119.69	2.00
Depth 5.3	5.70	18.94	75.36	379.79	3.21
Depth 5.6	4.30	18.13	77.57	196.48	2.85
Depth 5.7	5.31	18.34	76.35	202.22	2.10
Depth 5.9	6.57	24.40	69.02	151.05	1.89
Depth 6.1	13.69	44.80	41.51	55.91	1.10
Depth 6.3	7.30	31.98	60.73	93.86	2.95

Appendix C
X-Ray Diffraction

Sample: Willabrook Depth: 1.5 m.
Date Run: 20/05/2010. UoW # X5234

ID	Phase	Weight%
1	Quartz	73.6
20	Albite(low)	8.8
19	Orthoclase 1	4.2
116	Illite 1	1.1
8240	Kaolin, BISH12	10.5
82	Muscovite	0.9
84	Chlorite	0.9

Sample: Brogers Creek Terrace 1. Depth: 3.2 m.
Date Run: 20/05/2010 UoW # X5424

ID:	Phase	Weight (%
1	Quartz	44.6
20	Albite(low)	12.9
19	Orthoclase 1	4.4
116	Illite 1	1.4
8240	Kaolin, BISH12	26.7
82	Muscovite	8.7
84	Chlorite	1.4

Sample: Willabrook. Depth: 2.2 m.
Date Run: 20/05/2010. UoW # X5235

ID	Phase	Weight%
1	Quartz	88.5
20	Albite(low)	5.5
19	Orthoclase 1	1.3
116	Illite 1	1.3
8240	Kaolin, BISH12	3.3

Sample: Brogers Creek Terrace 1. Depth: 4.4 m.
Date Run: 20/05/2010 UoW # X5430

ID:	Phase	Weight %
1	Quartz	57.4
20	Albite(low)	20.7
19	Orthoclase 1	5.5
116	Illite 1	2.4
8240	Kaolin, BISH12	8.7
82	Muscovite	4.9
84	Chlorite	0.4

Sample: Willabrook. Depth: 2.5 m.
Date Run: 20/05/2010. UoW # X5236

ID	Phase	Weight%
1	Quartz	92.5
20	Albite(low)	3
116	Illite 1	1.9
8240	Kaolin, BISH12	2.6

Sample: Brogers Creek Terrace 1. Depth: 5.2 m.
Date Run: 20/05/2010 UoW # X5425

ID:	Phase	Weight %
1	Quartz	56.7
20	Albite(low)	24.9
19	Orthoclase 1	7.5
116	Illite 1	1.7
8240	Kaolin, BISH12	6.7
82	Muscovite	1.7
84	Chlorite	1

Sample: Brogers Creek Terrace 2. Depth: 2.6 m. Date Run: 13/07/2010 UoW # X5435			Sample: Brogers Creek Terrace 3. Depth: 1.5 m. Date Run: 14/07/2010 UoW # X5432		
ID:	Phase	Weight %	ID:	Phase	Weight %
1	Quartz	57.2	1	Quartz	50.2
20	Albite(low)	11	20	Albite(low)	15.2
19	Orthoclase 1	5.8	19	Orthoclase 1	3.5
116	Illite 1	3.2	116	Illite 1	4.1
8240	Kaolin, BISH12	16.8	8240	Kaolin, BISH12	15.7
82	Muscovite	2.4	82	Muscovite	7.2
84	Chlorite	3.6	84	Chlorite	4.1
Sample: Brogers Creek Terrace 2. Depth: 4.0 m. Date Run: 13/07/2010 UoW # X5426			Sample: Brogers Creek Terrace 3. Depth: 2.0 m. Date Run: 14/07/2010 UoW # X5433		
ID:	Phase	Weight %	ID:	Phase	Weight %
1	Quartz	48.9	1	Quartz	39.5
20	Albite(low)	16.6	20	Albite(low)	13.5
19	Orthoclase 1	9.8	19	Orthoclase 1	4.4
116	Illite 1	1.5	116	Illite 1	1.4
8240	Kaolin, BISH12	15.4	8240	Kaolin, BISH12	24.9
82	Muscovite	0.9	82	Muscovite	7.6
84	Chlorite	6.9	84	Chlorite	8.7
Sample: Brogers Creek Terrace 2. Depth: 4.4 m. Date Run: 13/07/2010 UoW # X5427			Sample: Brogers Creek Terrace 3. Depth: 2.5 m. Date Run: 14/07/2010 UoW # X5434		
ID:	Phase	Weight %	ID:	Phase	Weight %
1	Quartz	50.6	1	Quartz	48.8
20	Albite(low)	15.3	20	Albite(low)	11.9
19	Orthoclase 1	8.4	19	Orthoclase 1	7.9
116	Illite 1	1.4	116	Illite 1	4.4
8240	Kaolin, BISH12	17.4	8240	Kaolin, BISH12	18.8
82	Muscovite	3.5	82	Muscovite	3.8
84	Chlorite	3.3	84	Chlorite	4.3

Sample: Bendeela Hole 2. Depth: 2.0 m.
Date Run: 20/05/2010 UoW # X5231

#	ID	Phase	Weight%
1	1	Quartz	72.9
2	20	Albite(low)	17.1
3	19	Orthoclase 1	1.5
4	116	Illite 1	1
5	8240	Kaolin, BISH12	5.3
6	84	Chlorite	2.3

Sample: Cockrane’s Farm Hole 1. Depth: 3.3 m.
Date Run: 13/07/2010 UoW # X5428

ID:	Phase	Weight %
1	Quartz	48.6
20	Albite(low)	18.8
19	Orthoclase 1	4.6
116	Illite 1	2.3
8240	Kaolin, BISH12	19.8
82	Muscovite	4.5
84	Chlorite	1.5

Sample: Bendeela Hole 2. Depth: 3.9 m.
Date Run: 20/05/2010 UoW # X5232

#	ID	Phase	Weight%
1	1	Quartz	60.5
2	20	Albite(low)	13
3	19	Orthoclase 1	7.8
4	116	Illite 1	4.4
5	8240	Kaolin, BISH12	10.1
6	82	Muscovite	3.6
7	84	Chlorite	0.5

Sample: Cockrane’s Farm Hole 1. Depth: 4.7 m.
Date Run: 13/07/2010 UoW # X5429

ID:	Phase	Weight %
1	Quartz	55.1
20	Albite(low)	17.1
19	Orthoclase 1	5
116	Illite 1	3.9
8240	Kaolin, BISH12	10.1
82	Muscovite	7.4
84	Chlorite	1.3

Sample: Bendeela Hole 2. Depth: 5.5 m.
Date Run: 20/05/2010 UoW # X5233

#	ID	Phase	Weight%
1	1	Quartz	52.2
2	20	Albite(low)	18.3
3	19	Orthoclase 1	5.2
4	116	Illite 1	2.8
5	8240	Kaolin, BISH12	11.5
6	82	Muscovite	7.7
7	84	Chlorite	2.4

Sample: Cockrane’s Farm Hole 1. Depth: 5.9 m.
Date Run: 14/07/2010 UoW # X5434

ID:	Phase	Weight %
1	Quartz	57.7
20	Albite(low)	15.9
19	Orthoclase 1	2.2
116	Illite 1	6.6
8240	Kaolin, BISH12	12.6
82	Muscovite	2.1
84	Chlorite	2.8

Sample: Cockrane's Farm Hole 5. Depth: 1.4 m.		
Date Run: 20/05/2010 UoW # X5240		
ID	Phase	Weight %
1	Quartz	44.3
20	Albite(low)	15
19	Orthoclase 1	8.8
116	Illite 1	4.7
8240	Kaolin, BISH12	16.1
82	Muscovite	8.6
84	Chlorite	2.5
Sample: Cockrane's Farm Hole 5. Depth: 5.5 m.		
Date Run: 20/05/2010 UoW # X5241		
ID	Phase	Weight %
1	Quartz	70.4
20	Albite(low)	13.1
19	Orthoclase 1	3.4
116	Illite 1	4.4
8240	Kaolin, BISH12	8.7
82	Muscovite	0.1
Sample: Cockrane's Farm Hole 5. Depth: 6.9 m.		
Date Run: 20/05/2010 UoW # X5242		
ID	Phase	Weight%
1	Quartz	68.2
20	Albite(low)	9.3
19	Orthoclase 1	9.2
116	Illite 1	3.8
8240	Kaolin, BISH12	4.6
82	Muscovite	2.2
84	Chlorite	2.7
Sample: Cockrane's Farm Hole 5. Depth: 4.3 m.		
Date Run: 20/05/2010 UoW # X5243		
ID	Phase	Weight%
1	Quartz	75.7
20	Albite(low)	8.1
19	Orthoclase 1	6.1
116	Illite 1	0.9
8240	Kaolin, BISH12	5.3
82	Muscovite	3.8